Transactions

AMERICAN FOUNDRYMEN'S ASSOCIATION

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TRANSACTIONS

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The Fluidity of Ingot Iron and Carbon and Alloy Cast Steels*

By H. F. Taylor[1], E. A. Rominski[1], Washington, D. C., and C. W. Briggs[2], Cleveland, Ohio

Abstract

Studies are presented on the fluidity of cast steel as measured by various types of test pieces, including the spiral fluidity mold, which was found to give the most accurate and dependable results. The experimental technique, designed for as complete a control of variables as possible, is described in detail. A testing procedure is outlined whereby it is possible to use the spiral fluidity mold effectively at the furnace for determining proper tapping times. The preparation of the test mold, that is, whether it is made of cement sand or green or dried sand (bentonite bonded) has no influence of the fluidity of cast steel as measured by the spiral. The length of spiral, when cast in naturally-bonded, green, sand molds, is consistently longer than when cast in naturally-bonded, dried, sand molds. Mold washes decrease the length of spiral slightly but give better reproduction of the mold cavity. Temperature is a very important factor in governing the flowing power of steel and its relationship to fluidity is clearly shown for many compositions. Carbon content was found to affect fluidity to a small degree but the influence is not marked. The effect of deoxidation, as governed by the amount of deoxidizer added, indicates that a certain critical amount of oxide is necessary for maximum fluidity. The basic influence upon fluidity of elements, added for their alloying effect, is shown to be a function

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* Published by permission of the Navy Department.

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of the individual element and follows no predictable rule. Within the limits of the experiments, molybdenum, vanadium and chromium decreased somewhat the running quality of the steels to which they were added while copper and nickel increased it. It was found essential that silicon be maintained above a critical value, or supplemented by a suitable deoxidizer, in the interest of fluidity as well as soundness. Manganese, in the amounts usually employed in plain carbon steels, does not increase fluidity at normal pouring temperatures. When used in customary amounts in the presence of silicon, manganese neither increases nor decreases the spiral length perceptibly. When present in higher concentrations (medium manganese or Hadfield steels), manganese markedly increases fluidity at lower temperatures in proportion to the amount present.

INTRODUCTION

1. Since the beginning of the steel castings industry, the evaluation of the flowing power of molten steel has been an elusive and much discussed quantity. This quantity is variously referred to as "life," "fluid life," "castability," "runability," "shankability," "flowability," or "fluidity," each indicating the property of the metal which allows it to flow readily into a mold and fill it before such freezing occurs as would offer an obstruction to its flow.

2. Preference is given by the authors to the term "fluidity" since it satisfactorily depicts the casting quality of one steel relative to another and clearly describes this property to foundrymen. It has the disadvantage, however, that in the past it had a specific physical meaning; namely, the reciprocal of the coefficient of viscosity. In recent literature, "coefficient of liquidity" is preferred for this constant, thus allowing the broader field to be covered by the term "fluidity." There are many, however, who have not accepted the term in its new sense as old associations stand in the way of its adoption, and hence the terms given above are variously preferred.

3. When using "fluidity" in its broader aspects, it must be remembered that it should by no means be identified with viscosity. The viscosity of a fluid, in the physical sense, is concerned with movements in the interior of the liquid, and thus, at a given temperature, is a definite physical constant. The viscosity test, which is rather simple and accurate near atmospheric temperatures, is

exceedingly difficult to perform at the temperature of molten steel. Therefore, foundrymen have found it necessary to devise a more practical method for their studies of the flowing properties of molten steel. In general, this test consists of pouring the steel into sand molds which contain a cavity in the form of a spiral or straight channel, the measured length of flow being taken as the index of fluidity. This test is concerned primarily with the fluid life of the steel as influenced by all the quantities incident to the casting process, and measurements refer both to the metal and to the mold.

4. Such a test has never enjoyed much practical application in steel foundries. It has been common practice to judge fluidity by the appearance of the steel as it is handled on the floor. Steel melters usually judge fluidity by the appearance of the metal to the eye as it is poured slowly from a small hand ladle or by the number of seconds necessary for a film to form on the surface of the metal in a test spoon. When these simple tests are made regularly on the same type of steel by a conscientious and experienced melter, an approximate indication of its condition can be obtained. However, no concrete data from a useful experimental standpoint remain after the melter makes his estimate, and since the human equation varies from plant to plant, it is impossible to prevent misleading and conflicting observations.

5. From the testing of some 200 to 300 heats of steel of various analyses in the manner indicated in the text, it has become increasingly clear that the surface appearance of molten steel is not a dependable criterion of its ability to fill a mold. Many heats which appeared sluggish and dead from a superficial visual inspection proved to be superior in fluidity to others which seemed lively and brilliant. The emissivity, the degree of oxidation, and surface film characteristics, all of which influence visual methods of judging castability, vary with slight changes in melting practice or steel composition. Certainly in alloy steels, and often in plain carbon steels, these factors become influential and may vary considerably from heat to heat. Even regarding the relative fluidities of low, medium, and high carbon steels, there arise widely differing opinions among foundrymen.

6. Thus it is desirable that some testing method be developed and adopted for production use which will give comparative figures and which will take into consideration those effective quantities that escape visual observation.

7. An evaluation of the fluidity of steel is dependent on two major factors; (1) properties of the metal and (2) variables of testing. The factors relating to the metal are those of viscosity, surface tension, surface films, gas content, suspended inclusions, and the mode of solidification and crystallization. The variables of testing include the form of the test piece, the casting head, the properties of the mold, the rate of pouring, and the degree of superheat. All of the mold conditions, and certain of the metal conditions which lend themselves to study, are considered in this paper. The theoretical aspects, concerning the properties of the metal and variables of testing, are set forth fully in another publication by one of the authors.[10]*

8. In the research work on this subject, the following problems were carefully dealt with:

(a) Development of a satisfactory practical method for determining the condition of the steel in the furnace prior to tapping. For general foundry use, such a test obviously should not require complicated apparatus or temperature measuring devices and should form a permanent record, if possible. These considerations lead to a "test piece" which must meet the following requirements:

(1) The test piece must be capable of measuring accurately small variations in fluidity and yet faithfully evaluate maximum and minimum values which result from extreme conditions of temperature and composition.

(2) The mold must be simple, inexpensive, and convenient to prepare, easy to manipulate and direct reading. Accurate leveling should not be necessary and provision should be made for maintenance of a constant flow head or at least one varying within narrow limits.

(3) Results from the test piece should be reproducible.

(b) Securing information on the effect of alloying elements and molding and melting conditions upon the fluidity of cast steel. When determining the effect upon fluidity of such variables as temperature and the composition of the steel, certain details of experimental technique should be followed:

* Superior numbers refer to the bibliography appended to this paper.

(1) Direct temperature measurement of the steel at the instant of testing with an accuracy of $\pm 5°C.$ in the region of 1500°C. (2730°F.) and at least $\pm 8°C.$ at 1700°C. (3090°F.) should be possible at all times.

(2) Foundry technique should be maintained constant throughout the test work.

(3) A careful chemical analysis should be made on each heat of steel poured. If any element is likely to be lost by oxidation, samples should be taken at the beginning and at the end of the pouring operations.

REVIEW OF PREVIOUS STUDIES ON THE FLUIDITY OF CAST STEEL

General Observations

9. Attempts[5, 6] have been made to evaluate the fluidity of cast steel on the basis of the iron-carbon diagram, stressing the possibility that variations in liquidus and solidus temperatures might be governing factors. Except in so far as the liquidus temperature determines the degree of super-heat, it is hard to understand why any close relationship should exist. If the steel solidified slowly and uniformly "in vacuo" with no temperature gradients, such predictions would be valid. However, variations in the degree of deoxidation of steels would often mask any relationships of practical value that might otherwise exist.

10. Although the use of either the solidus or liquidus temperature as that of zero fluidity[5, 6, 9] provides a convenient reference point, it is believed that under the conditions of solidification in the mold, where high temperature gradients occur in the metal, that neither the solidus nor the liquidus can be considered as the point of zero fluidity. The presence of a few particles of solid as the melt falls below the liquidus temperature can hardly be operative in suddenly checking fluid flow. Likewise, flow does not continue unchanged until all the metal has become solid. Rather it would appear that, for practical purposes, the point of zero fluidity lies somewhere between the liquidus and solidus.

Methods of Expressing Fluidity-Temperature Relationships

11. There are several ways of expressing the relationship between the composition of cast steel and its fluidity. One method[5, 6, 9]

necessitates a knowledge of liquidus temperatures from which it is possible to determine the amount of super-heat throughout the range of testing temperatures. Fluidity, in units of test casting length, is then plotted against composition for temperatures 50 or 100°C. above the liquidus. Thus it is possible that the effect of increasing amounts of an element upon fluidity may appear negligible, even though the actual test casting length is increased at a given temperature, because there is a simultaneous lowering of the liquidus. Another objection to this method lies in the lack of knowledge of liquidus temperatures and the difficulty of their determination. On the other hand, practical foundrymen are not interested in degrees superheat. They wish to know only how well the metal will fill their molds.

12. Another method[6] of expressing the fluidity relationship is based on a consideration of the casting surface. One investigator noted on examining test spirals that their appearance was best at a fluidity of 12-in. spiral length. Hence, having associated the optimum casting appearance with a definite fluidity for the gate size used, curves were drawn showing the relation between temperature and the composition at this fluidity. Whether such values bear any relationship to actual castings with much larger sections than the spiral, can be proved only by test. Such a method seems of doubtful value, however, since it is probable that, with several tests taken at small increments of temperature, many of the spirals would differ little in surface appearance. Also the optimum appearance probably would depend largely upon composition.

13. The most common method for showing the relationship between fluidity, temperature and composition employes a separate curve for each composition with fluidity plotted against temperature. From such curves, it is possible to obtain data for constructing other diagrams which show the relationships in whatever manner desired. Several experimental points are necessary to establish these basic curves accurately and, in general, extrapolation is uncertain, particularly at higher temperatures where oxidation may give trouble.

Review of Previous Work

14. In 1931, Saeger and Krynitsky[2] working at the National Bureau of Standards, described a spiral type of test piece for measuring the fluidity of cast iron. Saito and Hayashi[1] seem to

have been the original proposers of the spiral-type flow channel in 1919, but it remained for the forementioned investigators to put the test on a working basis. This test has been accepted in America as the standard fluidity test for cast irons and non-ferrous metals.

15. Ruff[3] used the Bureau of Standards mold with various modifications of gating for a comparison of the flow characteristics of cast iron and steel. During the course of his work, prior to 1936, he found the piece satisfactory for measurements on cast iron, but abandoned its use for cast steel. While he was able to get a certain amount of pertinent information, the lack of agreement of experimental points led to the development of a new type (Fig. 1), which was recommended by him as a practical foundry tool. It employs a straight flow channel, $\frac{3}{16}$-in. diameter, with a simple downgate.

16. In 1936 Andrew, Percival, and Bottomley[5] and in 1938 Andrew, Bottomley, Maddocks and Percival[6] using a spiral test piece provided with a ferrostatic head control and overflow basin, found that, in general, variations in carbon up to 0.90 per cent increased the fluidity of cast steel but slightly if the fluidity at a particular temperature was considered. Silicon, manganese, copper, chromium, nickel and phosphorus were found to improve fluidity in proportion to the amount added. Complete analyses of the steels used for these investigations were not given.

17. Walker[8] compiled results from practical foundry trials using Ruff's test piece at the furnace and dipping metal out with a sampling spoon. His results were inconclusive, chiefly because of the lack of adequate means for measuring steel temperatures, but he indicated that the test would ultimately prove valuable in ensuring properly conditioned steel.

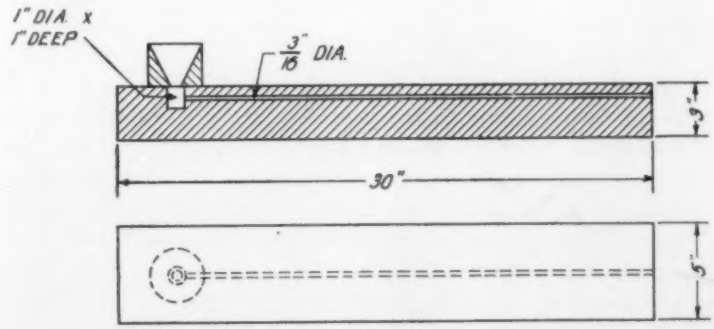


FIG. 1—DETAILS OF RUFF FLUIDITY MOLD FOR COMPARISON TESTS.

18. Prior to 1938 Sarjant and Middleham[9] employed a modified Ruff mold for experimental testing with an induction furnace of 20-lb. capacity. Later they made several fluidity tests using samples taken with a spoon from a basic electric furnace just prior to tapping, and from these concluded that "the method has the necessary simplicity and convenience for a works test." Fluidity-temperature data from their laboratory investigations, measuring temperatures with a tungsten-molybdenum thermocouple, yield the following conclusions:

(a) Swedish iron and Armco iron, of the same carbon, manganese, and silicon content, showed divergences in fluidity which were attributed to their differences in oxygen content.

(b) Carbon contents of 0.15, 0.43, and 0.83 per cent progressively increased fluidity.

(c) Additions of small amounts of aluminum (up to 0.30 per cent) confer increased fluidity on low-carbon steel.

(d) Copper (up to 2 per cent) improves the fluidity of cast steel with 1 per cent showing greater fluidity than 2 per cent.

(e) High manganese steels do not possess good fluidity at elevated temperatures.

19. In 1938 and 1939 Kron and Lorig[11] studied fluidity-temperature-composition relationships for cast steels of several analyses. They used a small 14-lb. furnace to pour straight rod test pieces, $\frac{7}{32}$-in. diameter in the manner proposed by Ruff. Their mold was an improvement over Ruff's, however, since it was equipped with a modified pouring basin to insure a regulated head of metal. The details of the mold are shown in Fig. 2.

20. From their experimental laboratory tests using this test piece, the authors claim "fairly consistent results obtained from the Ruff mold. Temperature-length of flow curves ran more or less parallel for steels containing varying amounts of carbon, manganese, silicon, and copper, and indicate that the flowing qualities of the steel were improved moderately by increased amounts of these elements. Titanium in the high manganese, high silicon, copper type cast steel appeared to affect the flowability adversely at high steel temperatures." Temperatures were measured with an

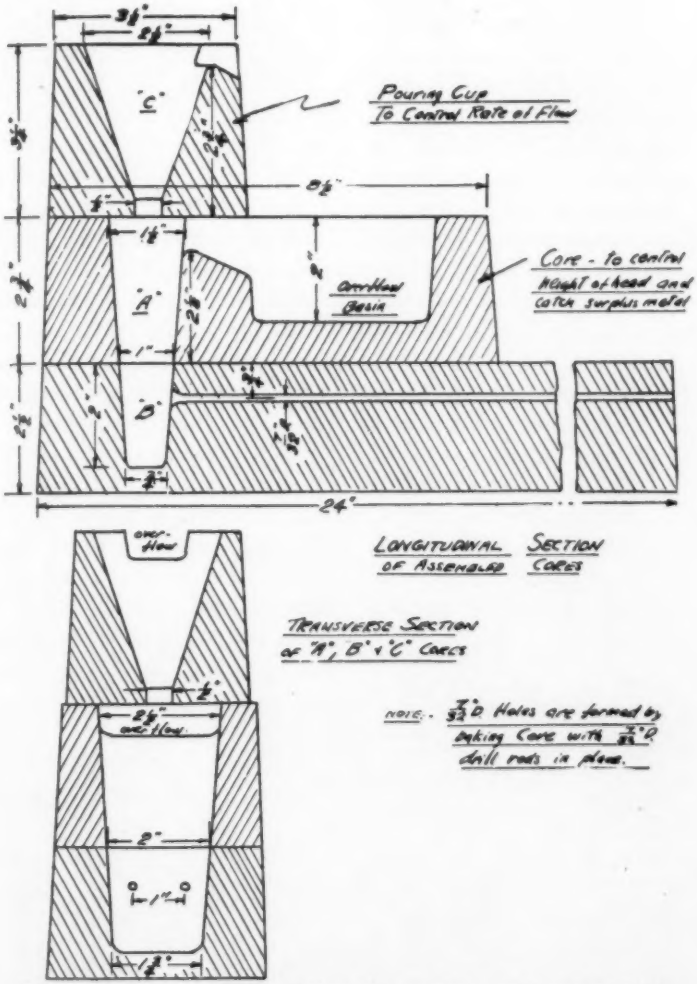


FIG. 2—DETAILS OF FLUIDITY TEST MOLD USED BY KRON AND LORIG[13] IN THEIR LABORATORY TESTS.

optical pyrometer sighted on the bottom of a closed end, clay-graphite tube immersed in the steel.

21. From the dispersion of results when using the simple flow channel Kron and Lorig saw the necessity for further reducing the effects of a variable metal head, turbulence, and inertia and of maintaining a uniform rate of pouring if the mold was to serve satisfactorily as a foundry tool for testing steel in the ladle. The small quantity of steel needed to fill the mold made it impossible

to obtain true values in a single test because of chilling of the steel by the cold ladle lip or nozzle. Figure 3 shows the details of the special mold designed for general foundry use. The flow channels were $\frac{7}{32}$-in. in diameter and the complete casting weighed approximately 110 lb. The mold was made of core sand, placed above a cast iron reservoir. The rate of pouring was regulated by the size of down sprue and an overflow on the catch basin. The large volume of metal flowing through the test block served to heat up the parts and also to insure testing metal at a temperature representative of the main body of steel in the ladle. This was a precautionary measure to eliminate the cooling effect of the ladle spout and mold surface on the metal as it was poured. As the cast iron receptacle filled, the steel necessarily rose to the level of the flow channels, filled them under conditions as free as possible from casting turbulence, and any excess metal escaped through a second overflow. Metal temperatures were taken with an optical pyrometer sighted on the bottom on a clay-graphite tube immersed in the molten steel and black body conditions were, therefore, assumed. This arrangement eliminated slag interference and possible variations in the emissivity of steels of different composition.

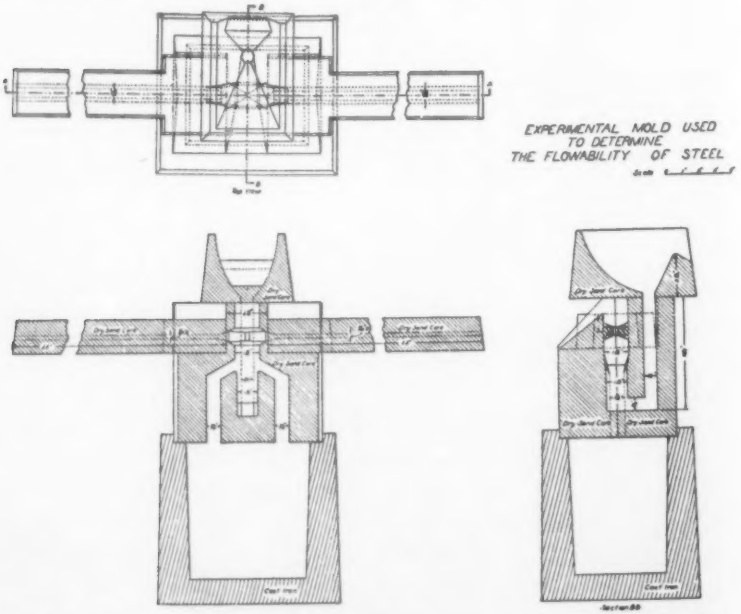


FIG. 3—DETAILS OF EXPERIMENTAL MOLD USED BY KRON AND LORIG[11] TO DETERMINE FLUIDITY OF CAST STEEL IN FOUNDRY TRIALS.

22. Using this apparatus, the technique of laboratory testing consisted of individual 120-lb. heats for each point determined. Three points were used in establishing a curve and six different analyses of steel were poured. The results have been replotted in the style used in presenting Naval Research Laboratory results and appear in Fig. 4.

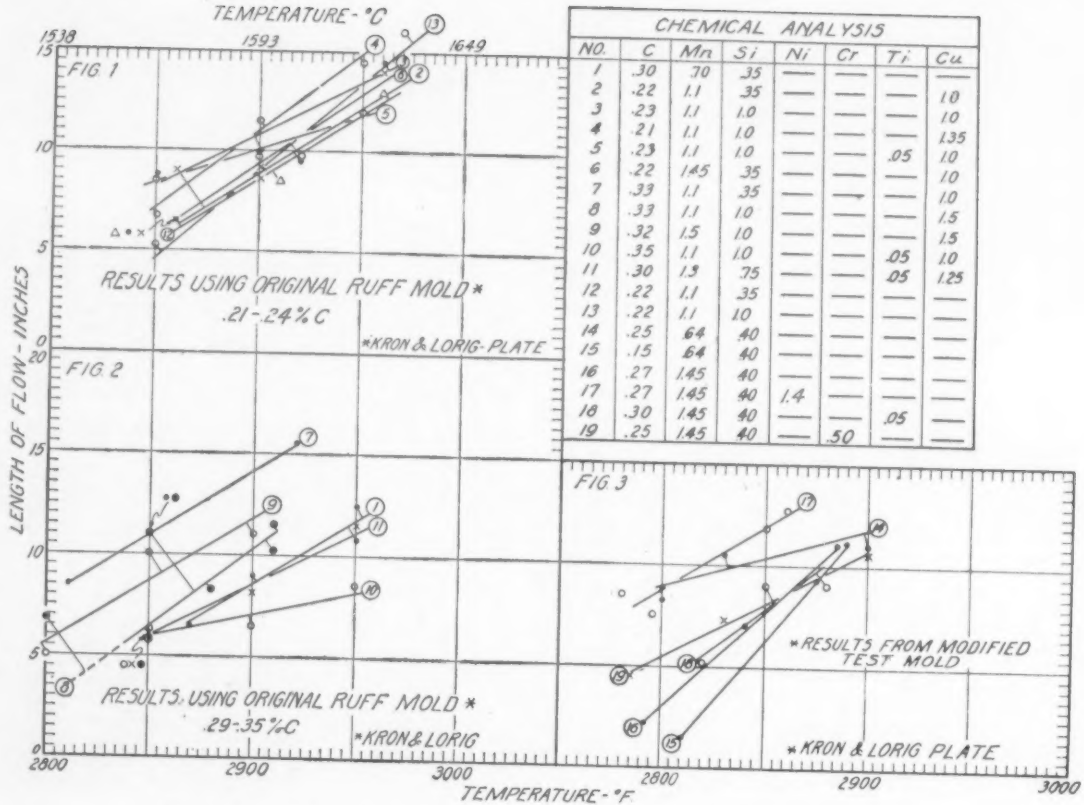
23. The curves constructed from the modified mold show considerably less dispersion of the experimental points than did those from the simpler type. From plant tests, the authors conclude that, under properly controlled conditions of temperature and pouring technique, the "mold described appears to have the necessary attributes for obtaining a reliable index of the flowing qualities of steel in the foundry."

24. Zeigler and Northrup[12] used the Saeger-Krynitsky spiral and Ash[13] used a slightly modified form, for testing cast iron to determine the influence of deoxidation, carbon content, temperature and degree of superheat on the fluidity of the metal.

25. Lips[14] has treated the fluidity of metals from a consideration of the flow conditions resulting from methods of gating, and shows clearly why certain types of ingates are to be preferred over others. He indicates the dependence of smooth and turbulent flow upon the runner diameter and shows why pouring gates should be designed on purely hydrodynamical principles, and should never be combined with a riser for purposes of feeding any part of a casting.

26. The results of the investigations on steel discussed above do not agree quantitatively, which is not surprising since different types of test pieces were used. Sarjant and Middleham used thermocouples to measure the temperature of the steel, but in several instances complete chemical analyses were not reported.

27. The effect of composition on the fluidity of cast steel apparently has been considered only from the standpoint of the basic alloying effect of the various elements, neglecting such variables as gas or oxide content. One of the chief reasons why fluidity predictions based on equilibrium diagrams are not valid, is because of the large variations possible in the state of oxidation of steel. Even if prepared under seemingly identical conditions with carbon, manganese, and silicon adjusted in the usual way, steels can vary widely in flow characteristics.



CHEMICAL ANALYSIS

NO.	C	Mn	Si	Ni	Cr	Ti	Cu
1	.30	.70	.35	—	—	—	—
2	.22	1.1	.35	—	—	—	1.0
3	.23	1.1	1.0	—	—	—	1.0
4	.21	1.1	1.0	—	—	—	1.35
5	.23	1.1	1.0	—	—	.05	1.0
6	.22	1.45	.35	—	—	—	1.0
7	.33	1.1	.35	—	—	—	1.0
8	.33	1.1	1.0	—	—	—	1.5
9	.32	1.5	1.0	—	—	—	1.5
10	.35	1.1	1.0	—	—	.05	1.0
11	.30	1.3	.75	—	—	.05	1.25
12	.22	1.1	.35	—	—	—	—
13	.22	1.1	1.0	—	—	—	—
14	.25	.64	.40	—	—	—	—
15	.15	.64	.40	—	—	—	—
16	.27	1.45	.40	—	—	—	—
17	.27	1.45	.40	1.4	—	—	—
18	.30	1.45	.40	—	—	.05	—
19	.25	1.45	.40	—	.50	—	—

FIG. 4—RESULTS OBTAINED BY KRON AND LORIG[13] USING FLUIDITY MOLD SHOWN IN FIG. 3.

28. Nearly all work appearing in the technical press to date has presented curves showing fluidity either strictly proportional to temperature or increasing toward infinity as the temperature increases. Ruff, however, determined from his studies that the effect of temperature upon casting length became progressively less in the higher thermal range. Other investigators missed this salient feature because too few experimental points usually were taken, these being confined to low temperatures. No doubt in many cases, the lack of adequate pyrometry was a contributing cause. Some steels vary markedly in their behaviour as temperature increases. Hadfield manganese steels, for example, are very fluid at low temperatures but sluggish at high temperature, when compared with plain carbon steels, and a pouring practice normally used for the latter may result in faulty castings. Such relationships are discovered only when fluidity measurements are made over the complete range of possible pouring temperatures.

METHODS USED IN TESTING

29. The fluidity mold used for obtaining the major part of the information presented in this report, was patterned after the Bureau of Standards spiral but modified in cross-section of flow channel and method of gating to fit the requirements of cast steel. The Bureau of Standards design was actually tried but the length of flow was too small and the reproducibility of results too poor to give the required information. Larger horn gates than the one prescribed were tried but such gates, in general, gave greater dispersion of experimental points than the straight down gate when used with steel. Spirals with flow channels of different cross-sections were studied as well as various styles of pouring reservoir. Figures 5 and 6 show the details of the modifications of the Bureau of Standards mold which were found necessary by experimental development.

30. The sand used for molding was washed and graded silica sand mixed to proportions of 92 per cent sand, 5 per cent bentonite, and 3 per cent water. A facing sand mixed to this formula, was used in all cases, unless otherwise noted, and after use went into the heap to be used as backing sand. Table 1 gives the average properties for both facing and backing sands. The mulling time for each mix was approximately 3 min., and the molds stood assembled from ½ to 2 hours before being poured. Green sand practice was used in all cases, except for the comparison tests using

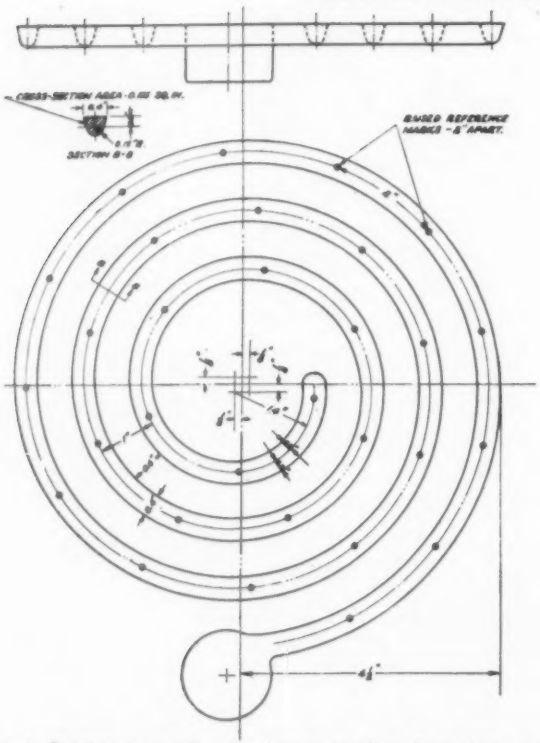


FIG. 5—DIMENSIONS OF FLUIDITY SPIRAL FOR CAST STEEL USED IN NAVAL RESEARCH LABORATORY INVESTIGATION.

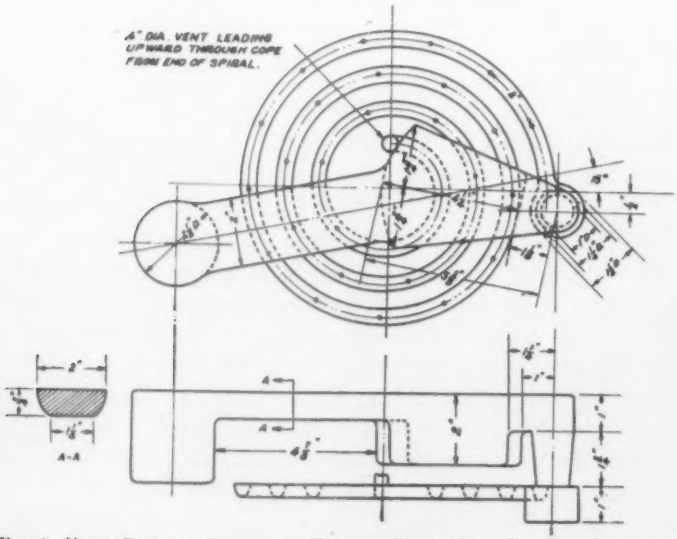


FIG. 6—NAVAL RESEARCH LABORATORY FLUIDITY SPIRAL WITH STRAIGHT DOWN-GATE AND MODIFIED POURING BASIN.

Table 1

SAND PROPERTIES

	Facing	*Backing*
Moisture, per cent	2.9 - 3.1	2.9 - 3.3
Compression Strength, lb. per sq. in.	5.5	5
Permeability	112	115
A.F.A. Grain Size No.	63	63
Distribution:	..	..
Sieve U. S. Standard	*Per Cent Retained*	
6	0	
12	0	
20	0.04	
30	0.26	
40	2.72	
50	12.50	
70	38.44	
100	31.78	
140	11.54	
200	2.22	
270	0.30	
pan	0.22	

dry and cement sand molds. The end of the spiral was vented to allow an easy passage of gas. Steel flasks (3-in. cope and 4-in. drag) with inside dimensions of 10 x 16 in. were used.

31. Figures 7 to 23 inclusive, showing the testing procedure, are largely self-explanatory and it is easy to follow the progress of metal during pouring. The metal is poured (Figs. 18, 19 and 20) into the runner guide and fills the catch basin to slightly above the lower overflow level. It then flows into the spiral evenly with a minimum of turbulence. A second overflow level, slightly higher than the first, regulates the variation in ferrostatic head during pouring, to ¼-in. The small overflow basin is provided to take care

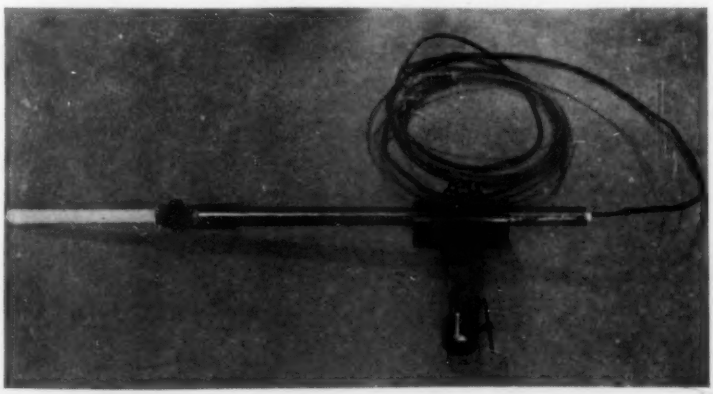


FIG. 7—THERMOCOUPLE ASSEMBLY READY FOR PREHEATING.

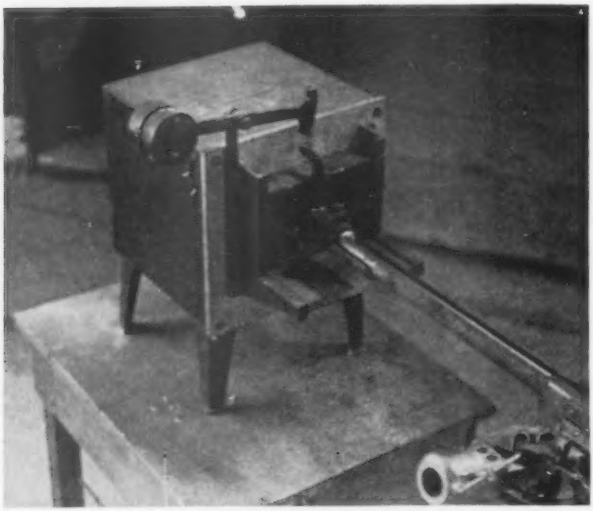


FIG. 8—PREHEATING THE THERMOCOUPLE.

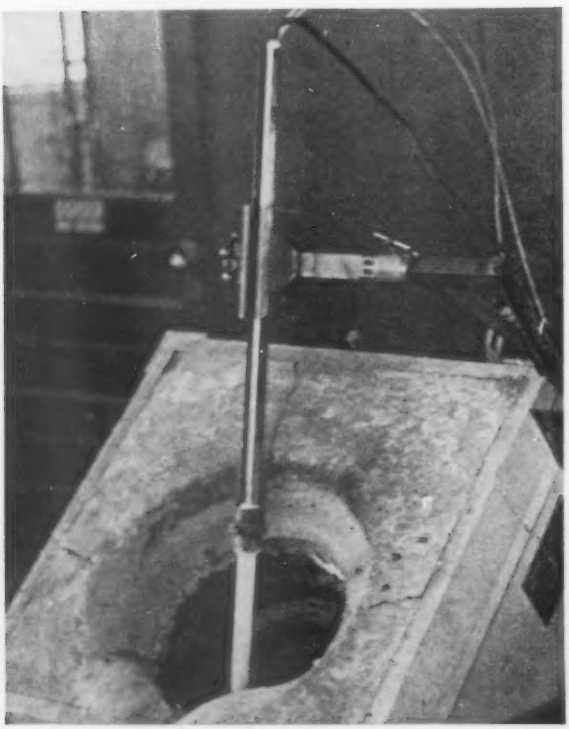


FIG. 9—PREHEATED THERMOCOUPLE AND ASSEMBLY MOUNTED TO BED FRAME.

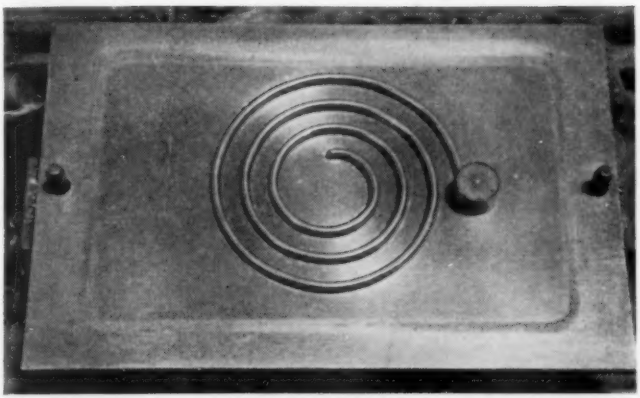


FIG. 10—DRAG SECTION OF FLUIDITY SPIRAL PATTERN, SHOWING BLIND RESERVOIR.

of excess metal. Small raised reference marks on the cope surface of the spiral are spaced accurately every 2 in. to facilitate checking the spiral length. Pouring rates were kept as nearly constant as possible and checked from time to time with a stop watch.

32. A few check heats were made with a 100-lb. basic lined furnace, but for most of the work a 300-lb., tilting-type, induction unit was used with a silica crucible: the pouring was controlled with a 500-lb. variable speed hoist. The melting stock was chiefly ingot iron and sheared S.A.E. 1015 steel. Melting stock previously made into round bars from the three-phase, electric-arc furnace was used for some of the test work. In some instances, the carbon content was adjusted with washed metal (3.55 per cent C.) and in others by the use of bars of technically pure graphite. The time required for melting a 300-lb. charge was normally 45 min., and the actual pouring of 20 molds involved approximately 30 min.

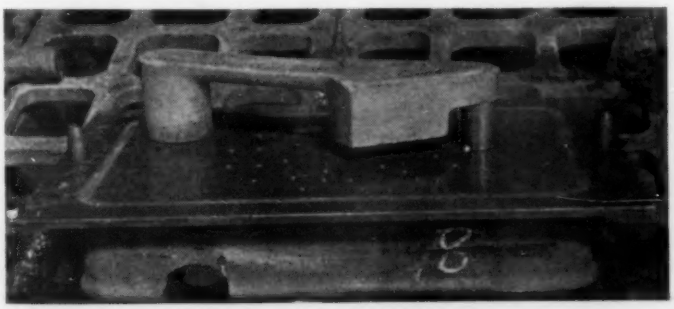


FIG. 11—COPE SECTION OF PATTERN WITH POURING BASIN IN PLACE AND SHOWING RAISED REFERENCE MARKS.

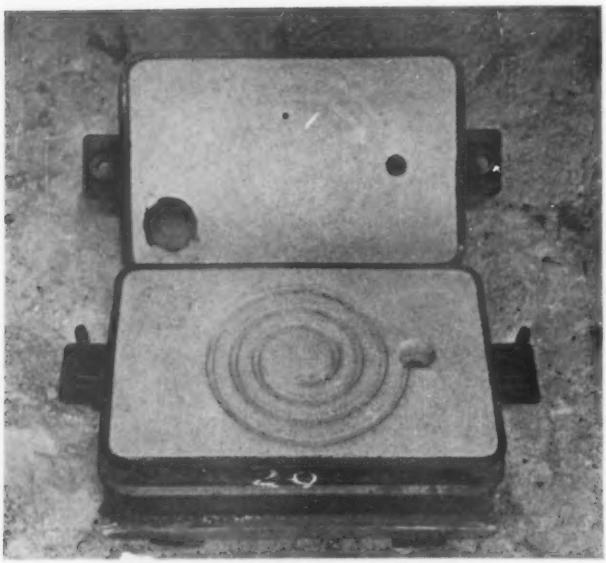


FIG. 12—SAND MOLD READY FOR CLOSING.

The slag was, for the most part, self-adjusting, with washed silica sand added as necessary.

33. Temperatures were measured with an 18-gage, tungsten-molybdenum thermocouple which was carefully calibrated against a National Bureau of Standards platinum-platinum 10 per cent rhodium type. The tungsten-molybdenum thermocouple was placed in a small fused quartz tube, about 30-in. long, which, in

FIG. 13—ASSEMBLED AND CLAMPED MOLD READY FOR USE.

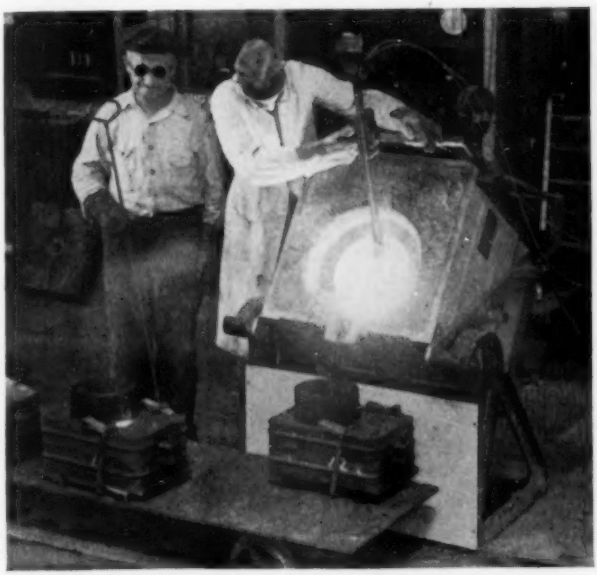


FIG. 14—ADJUSTMENT OF THERMOCOUPLE.

turn, was protected by a larger quartz tube 1⅛-in. outside diameter, 10-in. long, with not less than 0.15-in. wall thickness. This assembly (Fig. 7) was mounted in a holder and about 8-in. of the tubes were preheated in the small muffle furnace at 900°C. (1650°F.) to pre-

FIG. 15—RECORDING TEMPERATURES.

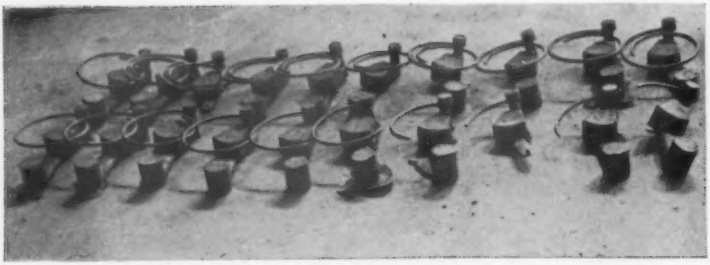


FIG. 16—SPIRALS READY FOR CHECKING LENGTHS.

vent cracking which might occur if the cold tube was suddenly immersed into the molten steel. When in use, the thermocouple hot junction was maintained at least 2½ in. below the surface of the steel, while the cold junction was kept several feet from the furnace.

34. A slip fit of the thermocouple holder on the bed frame permitted the tube to be moved freely in elevation. A second sliding fit at the base of the bed frame allowed complete adjustment in azimuth and a ratchet attachment enabled the tube to be fed deeper into the crucible as the volume of metal decreased when successive spirals were poured. The tubular part of the holder near the bath surface was constructed of heat resistant steel.

35. Certain curves, *i. e.*, the fluidity-temperature curves for ingot iron, (Fig. 31), indicate spirals being poured at temperatures seemingly somewhat below the melting point of iron of this purity.

FIG. 17—SINGLE FLUIDITY SPIRAL.

This can be explained only as a combination of experimental error and impurities in the metal. Temperatures always read slightly low because of the rapid heat conduction of the heavy walled quartz protection sheaths. It is believed that this error was constant throughout the work and that it does not detract from the value of the experimental results, since the comparative influence of the many variables tested is of primary importance. The error due to conduction along the protection tube is believed to be less than 5°C., and it decreases at higher temperatures where the accuracy of the pyrometric measurements falls to $\pm$8°C. Other factors contributing to the low apparent temperature of the ingot iron were the iron oxide concentration and other impurities, which might lower the solidification temperatures by as much as 15°C. Solidification studies made by freezing a thermocouple into the center of a 5-in. cube of ingot iron indicated 1512°C. (2755°F.) as the solidification temperature. Similar tests on the carbon and alloy steels checked the temperature of zero fluidity (indicated by extrapolation of the curves) much more closely than in the case of ingot iron.

36. Temperatures were also measured with two optical pyrometers of the rotating wedge type. Two experienced operators were stationed directly in front of the tilted bath at a distance of 10-ft. The stirring action of the current kept the bath surface free from slag which would otherwise interfere with the readings. No temperatures were taken on the flowing stream as too little time was involved in each test, but observations were made for each test point. The agreement between the two operators was surprisingly good, seldom varying by more than 10°C.

37. It was found that only for plain carbon steels (0.20 to 0.35 per cent carbon) did the optical pyrometer readings agree consistently with thermocouple indications. In such cases, the agreement was within 8°C. In other plain carbon steels and alloy types, differences of as much as 50°C. were not uncommon. Emissivity varies markedly with type and amount of alloy addition as well as with the state of deoxidation.

38. The compositions given in the illustrations are the actual chemical analyses. Usually three samples (shot) were taken for each heat, one after the melt down, a second following the final additions, and a third at the end of pouring. The analyses included only carbon, manganese, silicon, and whatever alloy was used. The

melting stock was checked from time to time and found to contain less than 0.04 per cent sulphur and 0.03 per cent phosphorus.

39. In all tests, unless otherwise noted, the method of temperature measurement, pouring height, melting and pouring practice, molding sand and test piece were all kept constant. If, for any reason, pouring speed or some other factor varied from standard practice for any test, the casting was discarded. It was found that the pouring speed could be varied within reasonable limits in testing with the fluidity spiral, however. The standard practice developed consisted in pouring from 10 to 20 spiral castings at temperatures between 1485 and 1700°C. (2705 and 3092°F.) with increments of 15° or 25°C. The molds were placed on a narrow gage, flat top truck (Figs. 18, 19, 20) and pushed along in front of the furnace as they were poured. As soon as the steel was melted and adjusted to the desired composition, the thermocouple was inserted and testing started. The thermocouple was kept in the bath continuously during the tests. In most cases, pouring was started at a low temperature and consecutive spirals were poured at chosen increments as the bath was rapidly heated to 1700°C. (3092°F.). The steady and easily regulated power input of the

FIG. 18—MOLDS READY FOR USE WITH TRUCK LOADED.

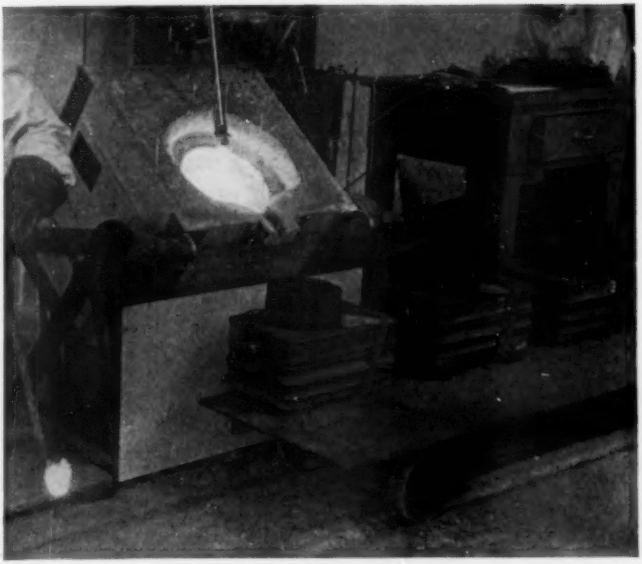


FIG. 19—TRUCK AND FIRST MOLD IN PLACE READY FOR POURING.

induction furnace made this procedure possible. The power input was kept high at the instant of pouring so as to keep the surface of the bath near the spout free from slag. Some tests were made

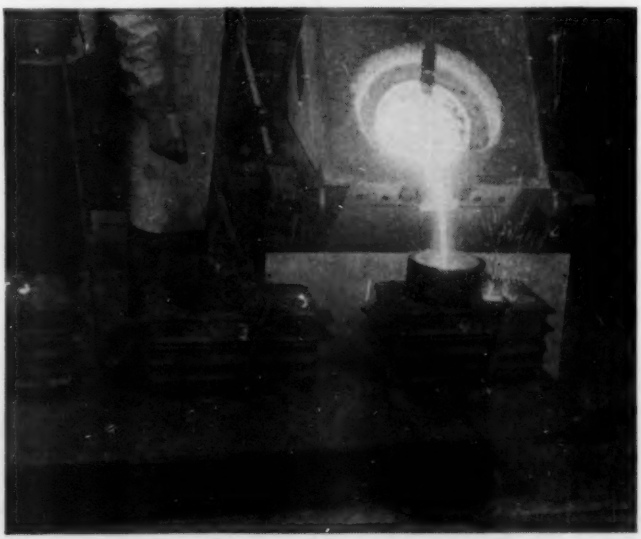


FIG. 20—POURING A FLUIDITY TEST MOLD.

FIG. 21—REMOVING THE FLUIDITY MOLD AFTER POURING.

by heating the bath rapidly to slightly above the highest temperature desired, making the final additions, and either turning the power off or maintaining it at a low level. The fluidity molds were

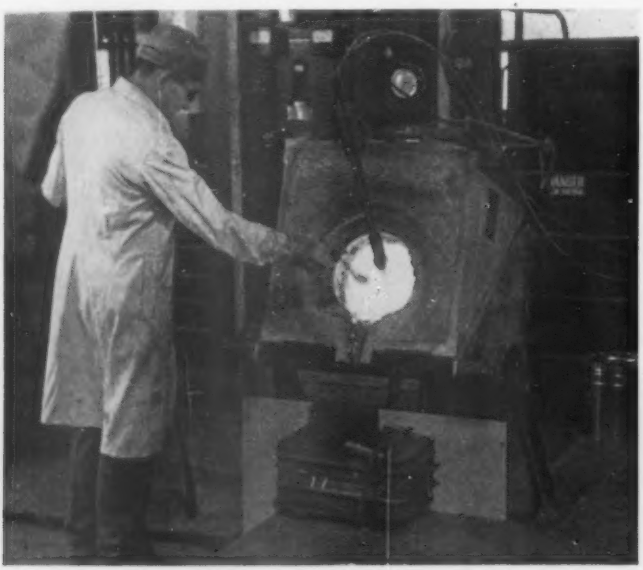


FIG. 22—ADDING FERROMANGANESE TO THE MELT.

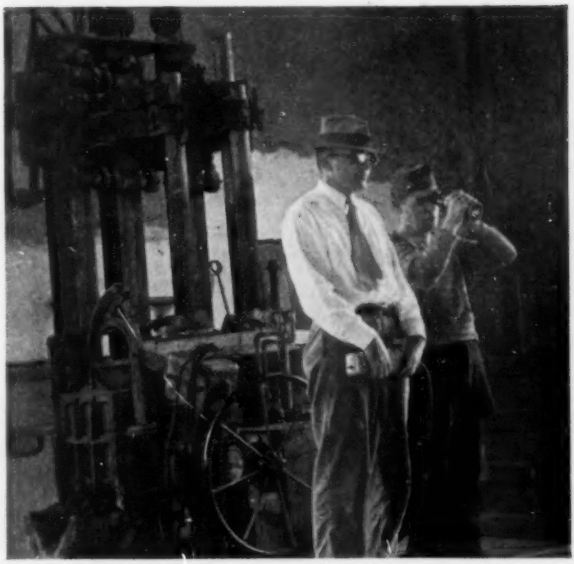


FIG. 23—HOIST OPERATOR AND OPTICAL PYROMETER OPERATOR.

then poured at chosen temperatures as the bath cooled. Increasing the current sharply at the instant of testing cleared the slag from the spout and stirred the bath to promote uniformity of temperature. Either method of testing was found fully satisfactory and spirals taken on heating and on cooling were in good agreement.

STUDY OF THE VARIABLES OF TESTING

Comparison of the Naval Research Laboratory Spiral, the Ruff Test Piece, and a Composite Test Piece including each Type.

40. An objection which can be made to the $\frac{3}{16}$-in. diameter, straight flow channel, designed and recommended by Ruff, (Fig. 1), is that it does not provide a controlled ferrostatic head. Also, the variation in length from minimum to maximum flow is too small to be a reliable index of small changes in fluidity. The temperature necessary to run 1.0 or 2.0 in. in a $\frac{3}{16}$-in. diameter channel is much higher than the temperature of zero fluidity. It has been found that castings can be poured from metal which fails to give a significant flow in a channel of this size. Finally, with the small volume of steel used for the test, there is a possibility that variables other than the castability of the metal may be more important than when a larger volume is used.

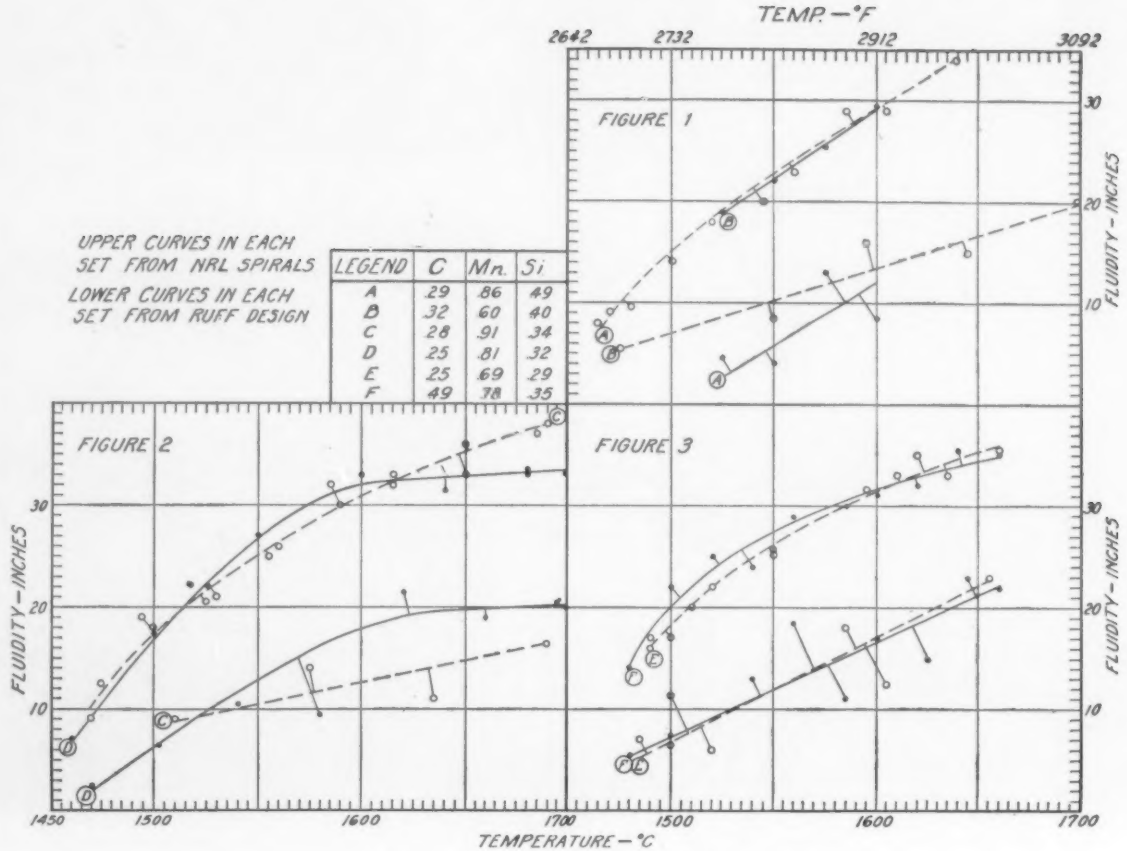


FIG. 24.—COMPARISON BETWEEN RUFF'S FLUIDITY TEST MOLD

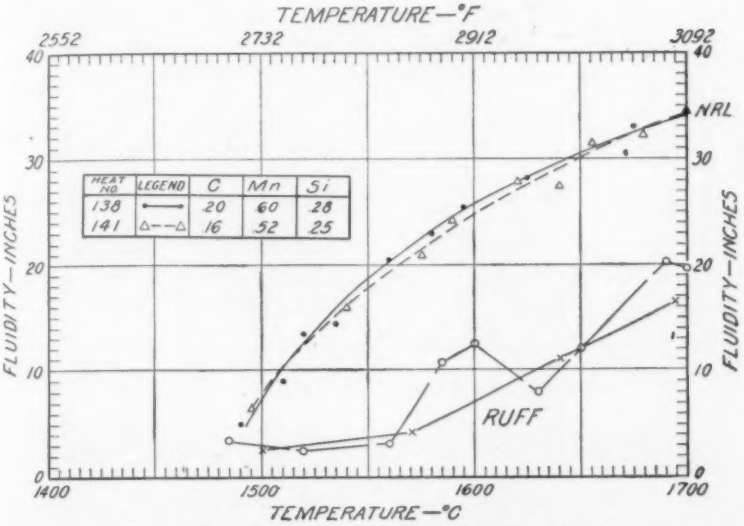


FIG. 25—SAME AS FOR FIG. 24 FOR TWO ADDITIONAL STEELS.

41. Comparison tests were made between the Ruff mold and the Naval Research Laboratory spiral (Figs. 5 and 6) by casting one immediately after the other at various temperatures. The results are shown in Figs. 24 and 25, and these indicate clearly the value of a controlled flow of metal. Comparison was also made between the Ruff type provided with a controlled ferrostatic head and the spiral test piece (Fig. 29).

42. Figures 24, 25, 50 and 54 give results of additional tests

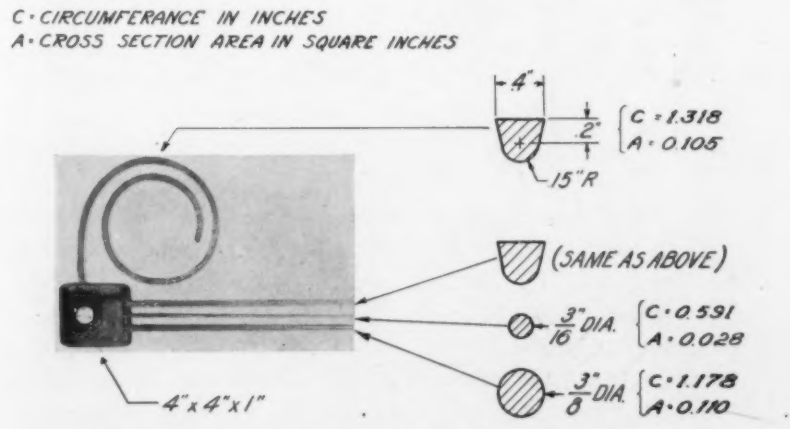


FIG. 26—DIMENSIONS OF INDIVIDUAL UNITS OF COMPOSITE TEST PIECE.

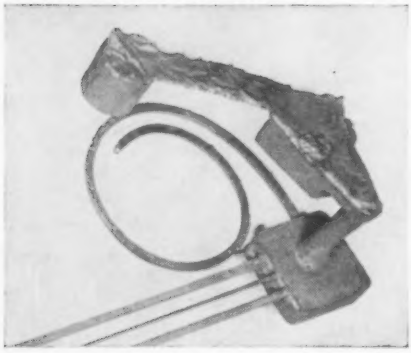


FIG. 27—POURING ARRANGEMENT OF COMPOSITE TEST PIECE.

made to compare the Ruff type of mold with the Naval Research Laboratory spiral. The superiority of the spiral as a test piece is shown not only by the longer runs but also by the better agreement among individual tests. Except for the very good curve shown in Fig. 50, the dispersion of points for the $\frac{3}{16}$-in. straight-flow channel is much greater than for the spiral.

43. To compare the different flow channels under the same pouring conditions, a composite test piece was designed. The detailed dimensions of the flow channels are shown in Figs. 26 and 27 and a series of castings made at various temperatures are shown in Fig. 28. The composite mold was designed to answer the following questions:

A. How does the length of run for the Ruff test piece compare with that for the Naval Research Laboratory spiral? Is this ratio constant and how is it affected by temperature?

B. What improvement would be made in the Ruff type fluidity mold by controlling the ferrostatic head within narrow limits?

C. What is the relationship between the Naval Research Laboratory spiral and a straight piece of the same cross-section and area?

D. How does such a test piece compare with a round straight piece of the same cross-sectional area since the round test piece has a smaller ratio of surface area to volume? In other words, will it give consistently longer runs because of its smaller surface area and consequently slower cooling rate?

E. Does a spiral attached to the composite piece give the same length as one poured separately?

F. Does a test piece cast in a straight flow channel show surface characteristics like those of the spiral test castings?

44. The results with the composite test piece (Figs. 26, 27, 28) using three heats of steel are shown in Fig. 29. A composite mold and a standard spiral test piece were poured in rapid succession at chosen temperatures. The molds were prepared with the regular sand-bentonite-water mixture and used in the green state; that is, molded and poured the same day. The spiral attached to the composite test piece was taken as the reference flow channel and the measured length of each of the other types was referred

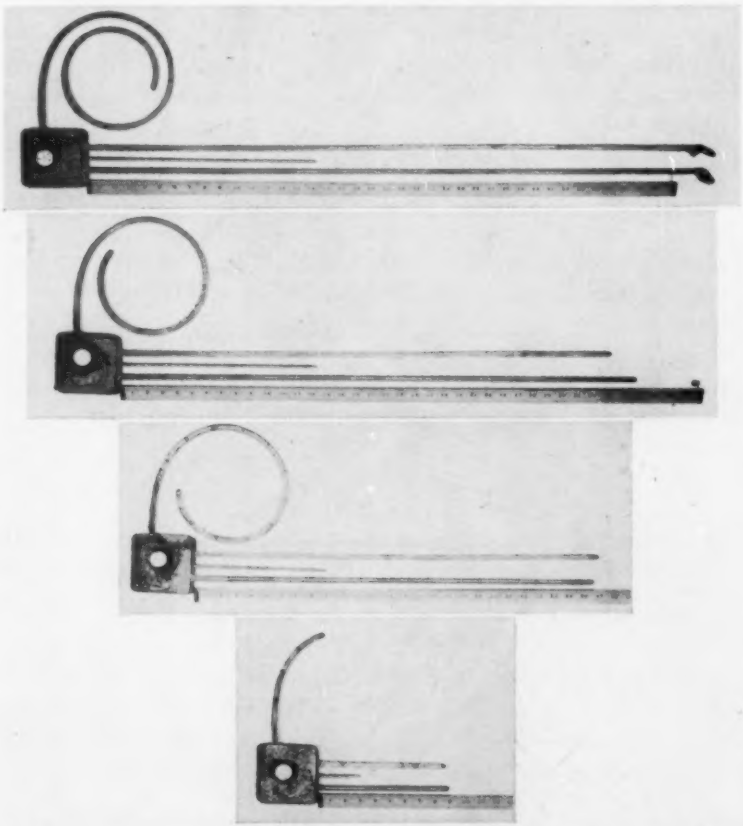
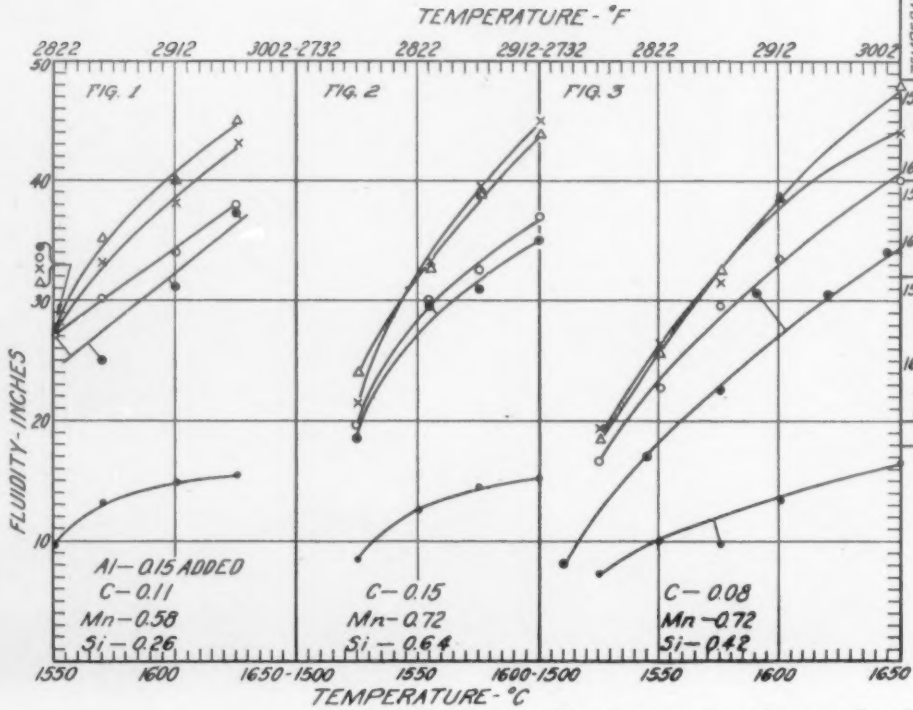


FIG. 29—COMPOSITE TEST PIECES POURED AT THE FOLLOWING TEMPERATURES: TOP—1625°C. (2955°F.) SECOND—1575°C. (2865°F.) THIRD—1550°C. (2820°F.) BOTTOM—1520°C. (2770°F.)



TEMPERATURE - °C	COMPOSITE TEST PIECE: ATTACHED SPIRAL — LENGTH - INCHES	ATTACHED SPIRAL — % OF ALT. SPIRAL	STRAIGHT MRL * FORM — LENGTH - INCHES	STRAIGHT MRL * FORM — % OF ALT. SPIRAL	STRAIGHT 3/16" DIA. ROD — LENGTH - INCHES	STRAIGHT 3/16" DIA. ROD — % OF ALT. SPIRAL	SEPARATE SPIRAL — LENGTH - INCHES	SEPARATE SPIRAL — % OF ALT. SPIRAL
1525	19.5	24	123	21.5	110	8.5	44	18.5	95
50	28.5	32	112	32.5	114	12.5	44	27	95
75	33	38	115	39.5	119	14.5	44	31.5	95
1600	37	44	119	45	121	15	41	35	95
1550	27	27	100	27	100	9.75	36	24	89
75	30.5	35.5	116	33.75	111	13.5	44	28	92
1600	34	40.75	120	38.5	113	14.75	43	32.25	95
25	38	45	118	42.75	113	15.5	41	36.25	95
1525	16.5	18.5	112	19.75	120	7.25	44	12.5	77
50	23.5	26	111	26.25	112	10	43	18.25	78
75	28.5	33	116	33	116	12	42	23	81
1600	33	38.5	117	37.75	114	13.5	41	27	82
25	37	43.5	118	41.5	112	15	41	31	84
50	40.5	48	118	44	109	16.5	41	34.5	85
	100		115		113		42		89 AVE.

LEGEND
- RUFF - 3/16" DIA. STRAIGHT
- SEPARATE SPIRAL
- ATTACHED SPIRAL
- × 3/16" DIA. ROUND-STRAIGHT
- △ SPIRAL X-SECTION-STRAIGHT

FIG. 29—COMPARISON OF FLOW CHANNELS USING COMPOSITE TEST PIECE.

to it in comparing the lengths of flow. These ratios are given in the table of Fig. 29 and the agreement among the three heats is believed good enough to make further tests unnecessary.

45. From this table, and from the curves, it may be seen that the $\frac{3}{16}$-in. diameter straight flow channel gives lengths of flow which are 42 per cent of the length of the attached spiral. This permits a comparison to be made between the results of foundries using the Ruff or the Battelle test piece and of those using the spiral type. The shorter length of flow obtained with the smaller flow channel limits its applicability and does not give significant lengths of flow at low temperatures, or with sluggish metal. The average value of 42 per cent varies slightly with the temperature. For example, the $\frac{3}{16}$-in. channel appeared to decrease from 44 per cent of the length of the attached spiral at 1525°C. (2777°F.) to 41 per cent at 1650°C. (3002°F.). In plant tests, the small flow channel often fails to show a significant length of run at temperatures where the steel still possesses enough fluidity to fill certain types of molds. The $\frac{7}{32}$-in. diameter channel used by Kron and Lorig would be slightly more effective in this respect than the $\frac{3}{16}$-in.

46. If the curves for the Ruff type, obtained from the composite test piece, are compared with those from the simple type, it can be seen that there is less scatter of points for the mold provided with the controlled head. This improvement is not necessarily due to the effect of ferrostatic pressure alone as this is of small consequence, but is in large part due to the evenness of flow of the molten metal into the test piece. The smoothness of the curves of Fig. 29 and the constancy of the ratio of flow lengths indicate that, under controlled conditions, both test pieces measure accurately the fluidity of cast steel. The spiral, however, is better adapted to routine foundry use where levelling and the sensitivity of the test piece are important.

47. The straight flow channel, with the same cross-section as the Naval Research Laboratory spiral, had an average length of run 115 per cent that of the attached spiral. This greater length shows that some resistance to flow was set up by the constantly changing direction of the spiral. However, this resistance is not great enough to affect the dependability of the spiral as a test piece.

48. The results of using a round flow channel of the same cross-sectional area as the spiral did not show that the slightly greater ratio of surface area to volume had any effect. In fact,

instead of this test piece giving a longer run than the trapezoidal-shaped, straight, flow channel, it was actually about 2 per cent shorter (113 per cent of the length of the attached spiral as compared with 115 per cent for the other). This difference is within experimental error and it is evident that the change in ratio of surface area to volume of the two pieces was too small to have any effect. Also, it appears that the shape of the section in a piece so small is unimportant.

49. When the length of the spiral attached to the composite test piece is compared with an identical spiral poured separately, it is found that the standard spiral was consistently shorter, its length being only 89 per cent that of the attached piece. This decrease is due to the velocity head which the metal acquired in falling 3½-in. in the composite test piece as compared to 1¾-in. in the standard test piece. Also, the shape and size of the header probably had some effect on the increased length of spiral.

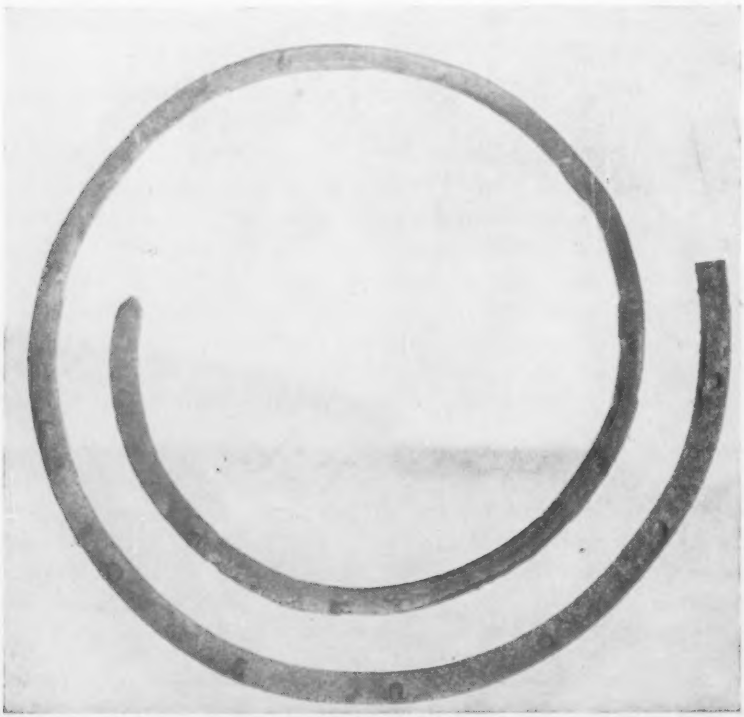


FIG. 30—TYPICAL SPIRAL SHOWING INCOMPLETELY-FILLED CENTRAL SECTION.

50. Certain surface characteristics, often noticed on the various spiral castings, seemed to recur with great regularity. For example, the surface of the spiral was smooth and gave a faithful reproduction of the mold cavity for several inches from the pouring button. Then an irregular and incompletely filled portion extended for several inches and finally the surface became like it was at the beginning. This smooth surface and well-filled section extended to the end of the spiral. These surfaces may be seen in Fig. 30. The central, poorly-filled portion of spiral showed a rippled appearance, and in many cases, the counting marks were missing. For a long time, it was thought that this peculiar behavior might be caused by the spiral design of the flow channel. However, the same tendency was found in the straight bar sections so the cause evidently lies in the properties of the flowing stream of metal.

The Reproducibility of Results Using the Spiral Test Piece

51. Figures 1 and 2 of Fig. 31, as well as Figs. 32, 47 and 49, show the reproducibility of the test piece and of the testing procedure under widely different experimental conditions. Data from control heats, made with three different shipments of ingot iron to check their suitability as a base material, are given in Fig. 2 of Fig. 31. The tests were made approximately eight months apart.

52. Figure 2 of Fig. 31 shows the results of three heats of ingot iron. The dispersion of points in each of the above tests is small for test work of this nature. The same number of molds were not always used for each test series, as many times part of the metal was used for other purposes. Also, occasionally a test casting was discarded if there was some obvious reason for doing so, such as a run out, a partly plugged flow channel, or an improperly run casting due to pouring short or to other faulty technique.

53. Figure 32 shows a fluidity-temperature curve for medium carbon steel and also control curves for five different heats of steel of similar analysis. For convenience, this curve will be called the "standard" curve, as it represents the fluidity of a steel most familiar to foundrymen. The control curves were obtained from different heats from time to time as a check on the testing technique to be sure that all variables were under control. For example, if fluidity tests were desired on a particular alloy steel, the carbon, manganese, and silicon contents were adjusted immediately after

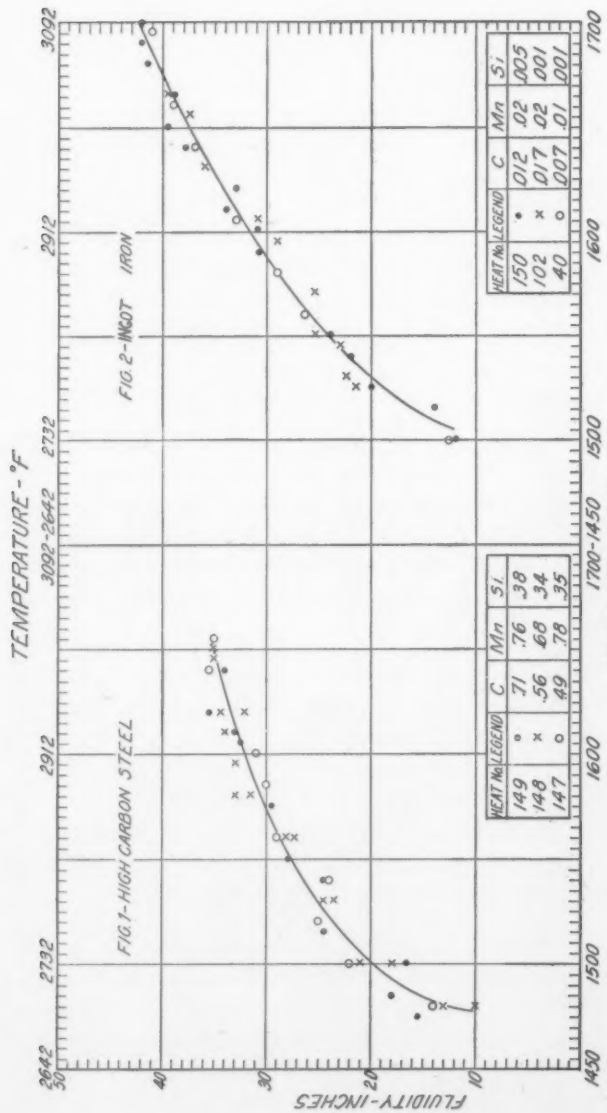


FIG. 1-HIGH CARBON STEEL
FIG. 2-INGOT IRON
TEMPERATURE - °F
TEMPERATURE - °C
FLUIDITY - INCHES
HEAT No | LEGEND | C | Mn | Si
149 | • | .71 | .76 | .38
148 | × | .56 | .68 | .34
147 | ○ | .49 | .78 | .35
HEAT No | LEGEND | C | Mn | Si
150 | • | .012 | .02 | .005
102 | × | .017 | .02 | .001
40 | ○ | .007 | .01 | .001

FIG. 31—CURVES SHOWING ABILITY TO REPRODUCE RESULTS.

HEAT NUMBER	POURING TEMP.—°C	SPIRAL LENGTH—INCHES
158	1525	17¾
	1550	24
	1575	27
	1600	31
159	1525	18
	1550	22
	1575	27
	1600	31
161	1530	19½
	1550	23
	1575	27
	1600	30

HEAT NUMBER	POURING TEMP.—°C	SPIRAL LENGTH—INCHES
162	1525	19
	1550	22
	1575	25¼
	1600	30¼
176	1480	7
	1500	11
	1520	18
	1540	23
	1560	24
	1580	27
	1600	32
	1620	34
	1640	33
	1660	35½

HEAT NO.	MELTING STOCK	LEGEND	C	Mn	Si	Ni
158	S.A.E. 1015	•	.24	.77	.33	—
159	S.A.E. 1015	×	.18	.74	.35	—
161	ELECT. FURN.	△	.23	.71	.37	.87
162	ELECT. FURN.	○	.27	.78	.50	.87
176	S.A.E. 1015	⧗	.30	.75	.41	—

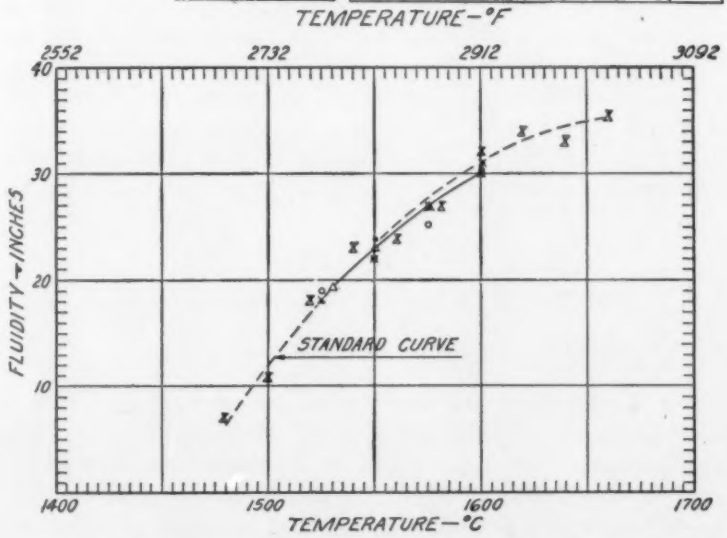


FIG. 32—CONTROL SERIES COMPARED WITH "STANDARD" CURVE.

the melt down and four or five spirals poured at definite increasing temperatures to establish the base or control curve. The alloy additions were then made and the testing continued in routine fashion. It is evident from Fig. 32 that excellent duplication of results can be obtained since the five heats gave curves which, for all practical purposes, are identical.

54. Additional evidence for the excellence of the checks obtainable with the Naval Research Laboratory spiral is given in

Figs. 48, 50 and 54. These tests were made for the purpose of confirming the data on the effect of alloying elements on fluidity. The procedure was as follows: four spirals were poured before any alloying additions were made in order to check the experimental conditions and to establish the base curve; the bath was then held at constant temperature and successive additions of the alloying element were made and tests were poured in duplicate after each addition. The exact composition desired was not always realized, since in calculating the amount of alloying element to be added, an estimate must be made of the metal poured in the preceding tests. Thus with a single melt, this procedure gives a satisfactory check on the results for five or six different compositions.

55. For the study of copper (Fig. 50), the temperature was held at 1630°C. (2966°F.) and Ruff-type, $\frac{3}{16}$-in. straight, bar test pieces were poured as well as spirals. The temperature selected for checking the manganese series was 1530°C. (2785°F.) as representative of the low range and that at which the fluidity-temperature curves (Fig. 3) for the various manganese contents leveled off for the high range. A similar check heat was made with molybdenum (Fig. 54).

THE EFFECT OF MOLD AND OTHER VARIABLES

Effect of Pouring Height

56. To determine the efficiency of the constant head feature of the spiral, molds were poured with the pouring spout 10-in. above the top of the cope, while at the same time others were poured from a height of 2-in. The curves plotted from the data (Fig. 33) show that no appreciable change in length of spiral was caused by this variation in pouring height.

Effect of Pouring Speed

57. The effect of pouring rate on the length of the fluidity spiral was studied and the information is set forth in Table 2. It may be seen that, if a pouring speed be maintained which will fill the mold in 2 or 3 seconds, consistent data will be obtained. On a pouring schedule of 20 molds, the operator was found to be within the above time limits on an average of at least 18 molds.

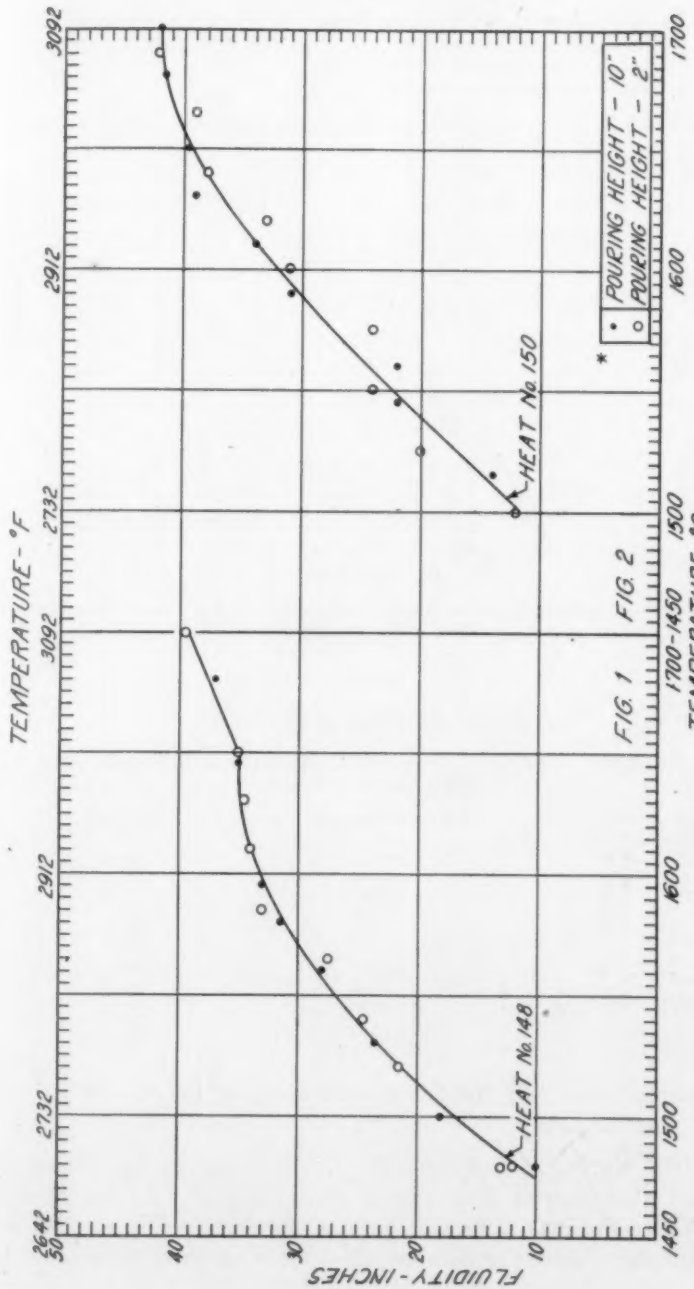


FIG. 38—INFLUENCE OF POURING HEIGHT ON LENGTH OF SPIRAL.

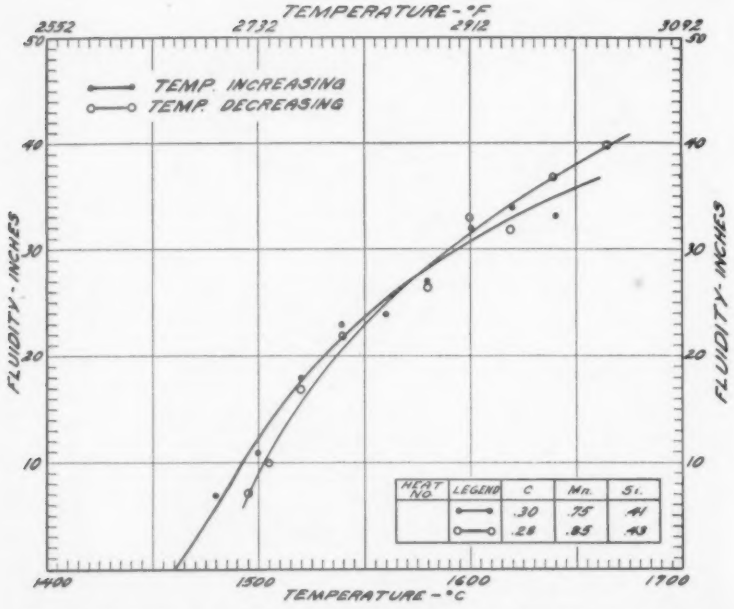


FIG. 34—DIFFERENCE IN CURVES RESULTING FROM TAKING DATA ON INCREASING OR DECREASING TEMPERATURES.

Table 2

STUDY OF RATE OF POURING

Analysis: Carbon, 0.27 per cent; Manganese, 0.60 per cent; Silicon, 0.32 per cent.

Pouring Speed, Sec. to Fill Mold	*Temperature, °C.*	*Fluidity, in.*
1.0	1570	30.5
1.3	1570	29.5
1.7	1570	28.0
2.2	1575	26.0
2.5	1575	26.5
2.5	1575	26.0
3.0	1580	25.0
3.5	1580	24.5
4.0	1578	22.0

Influence Upon Test Results of Increasing or Decreasing Bath Temperatures

58. Figure 34 compares the fluidity-temperature curves obtained when heating and when cooling the bath. As can be seen there is very little difference and results from either method are comparable. Since the data required for a series of tests could be

obtained in a much shorter time when the bath was steadily increased in temperature, this technique was preferred.

Effect of Green Sand, Dried Sand, and Dried and Washed Sand for Making the Molds

59. Except for variations in the sand mix, molds for steel work normally fall into two classes—green sand and dry sand.

60. A series of molds were prepared to determine the effect of differences in mold preparation on the fluidity of cast steel as measured by the spiral. Twelve molds were prepared of a sand-bentonite-water mixture suitable for dry sand work and were dried assembled in a core oven. It is necessary to dry the cope and drag in position to prevent finning. Six of these molds then were opened, a silica flour mold wash applied and again dried. On the following day, six green sand molds were prepared in the regular manner and the 18 molds poured in sets of three. Each set of three molds was lined up in turn on the pouring truck and poured as rapidly as possible to avoid any change in temperature of the steel. From Fig. 35, it can be seen that there was no differ-

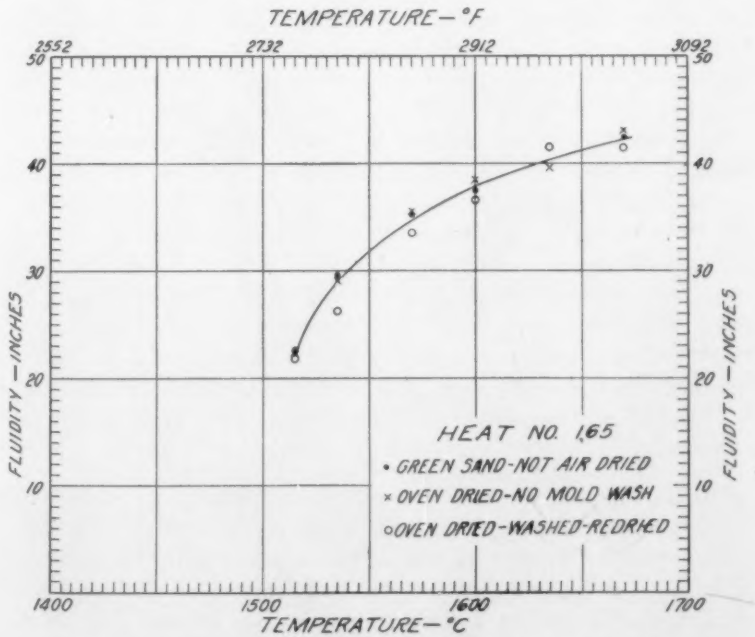


FIG. 35—INFLUENCE ON MOLD PREPARATION ON THE FLUIDITY OF STEEL.

Table 3

TESTS ON NATURALLY-BONDED GREEN AND DRIED SAND

Pouring Temperature °C.	°F.	*Fluidity, in.*	*Mold*
1570	2858	20½	Dry
		23¼	Green
1575	2867	22½	Dry
		24¼	Green
1600	2912	23	Dry
		30	Green
1625	2957	24	Dry
		28	Green
		27	Green
1650	3002	26½	Dry
		31	Green

ence whatever between the spirals poured in dry sand and those poured in green sand. This is in agreement with past experience at this laboratory using the spiral at the arc furnace. However, the washed molds gave spirals which were 2-in. shorter than those poured in green or unwashed dry sand. It was observed that the surface of the spirals from the washed mold was smoother than that from the others and that the washed mold gave a more faithful reproduction of the mold cavity. The washed surface may have lowered fluidity by increasing surface tension or by otherwise modifying the surface films, or the more complete filling of the spiral section may have caused a better heat transfer to the mold which resulted in a more rapid rate of cooling. Also the dried wash may have a higher coefficient of heat transfer than plain sand. That the surfaces of the dry sand and green sand specimens were much alike in appearance and length, indicates that the moisture in the green sand had no adverse effect. Photographs of typical spirals (Fig. 36) show the differences in surface appearance.

61. The above results are quite surprising as dry sand molds are commonly thought to be better than green sand molds in their effect upon the fluidity of steel. It is believed that the green and dried sand molds gave equal spiral lengths because of the inherent tendency of bentonite bonded green sand to become dry on the surface. The moisture from the backing sand does not migrate

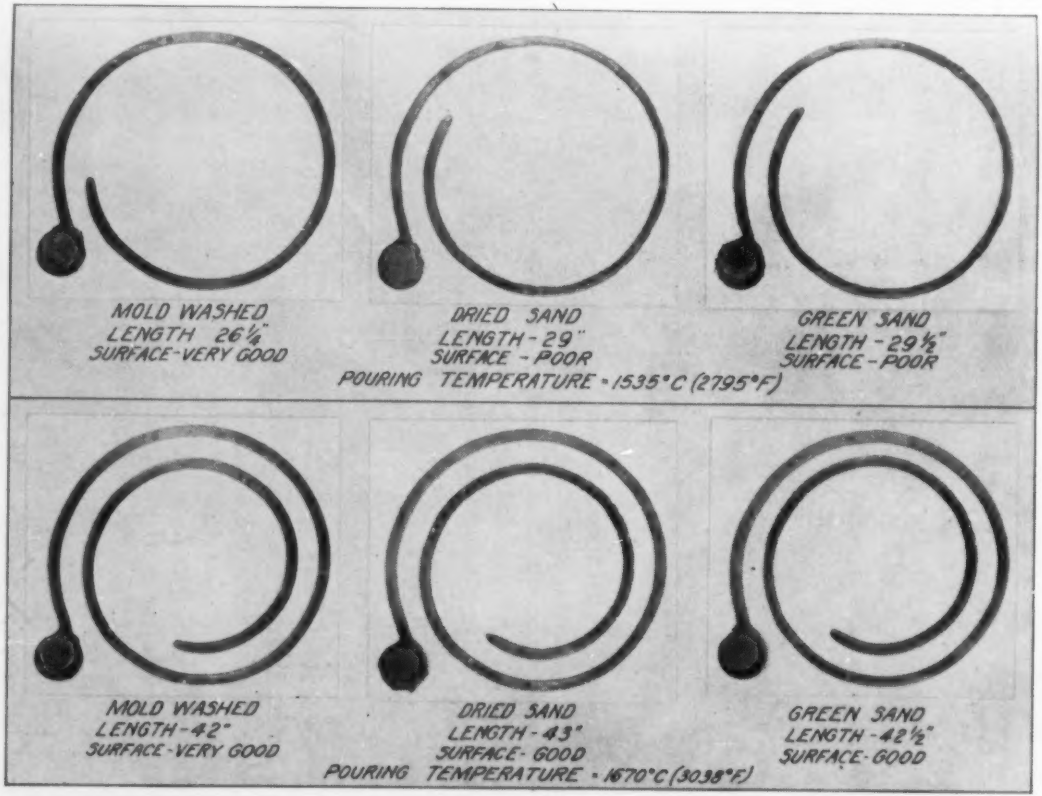


FIG. 36—INFLUENCE OF MOLD PREPARATION ON LENGTH AND SURFACE APPEARANCE OF SPIRALS OF CAST STEEL.

readily to the surface to replace that which evaporates and the interface between mold and metal for the time necessary to run the spiral acts as a dry sand mold.

62. Naturally-bonded green and dried-sand molds were tested to compare their relative effects upon fluidity and instead of the expected decrease in length of flow for the green sand the spirals were actually longer. Table 3 shows the results of tests made by pouring a mold of each type in rapid order at the indicated temperatures. In some cases, the green sand mold was poured first and in others the dry sand. Probably the enhanced length of flow is due to a layer of gas formed at the interface which acted as a cushion and also as an insulator for the short time necessary to flow the spiral. The behavior would undoubtedly be influenced by the amount of moisture present in the natural sand molds.

Effect of Cement Sand Molds

63. Because of the increasing use of cement sand as a molding material, the influence of this medium on the fluidity of cast steel is of interest. Figures 1 and 2 of Fig. 37 give the results of tests using spirals poured alternately in green-sand and cement-sand molds. The green-sand molds were made in the usual manner and the regular pouring technique employed. As might be anticipated, the cement sand behaved in the same way as ordinary dry sand, the lengths of spiral being the same as those made in green sand.

Effect of Sand Grain Size

64. It frequently has been stated that differences in sand grain size influence the ability of steel to fill castings with thin sections. To test this, molds were prepared as indicated in Fig. 38. The sands used varied in A.F.A. grain size from 53 to 123. The 63 sand was chosen as the standard for comparison, since it was regularly used for test work in the foundry. The molds were poured in pairs, each pair including a standard.

65. The curve of Fig. 38 shows little dispersion of points and indicates no definite influence of sand grain size. The variations which were observed are within the limits of experimental error. The flow channel used in the tests was small enough to permit any differences of mold preparation to exert their maximum effect. The data show that grain size has little effect, and this

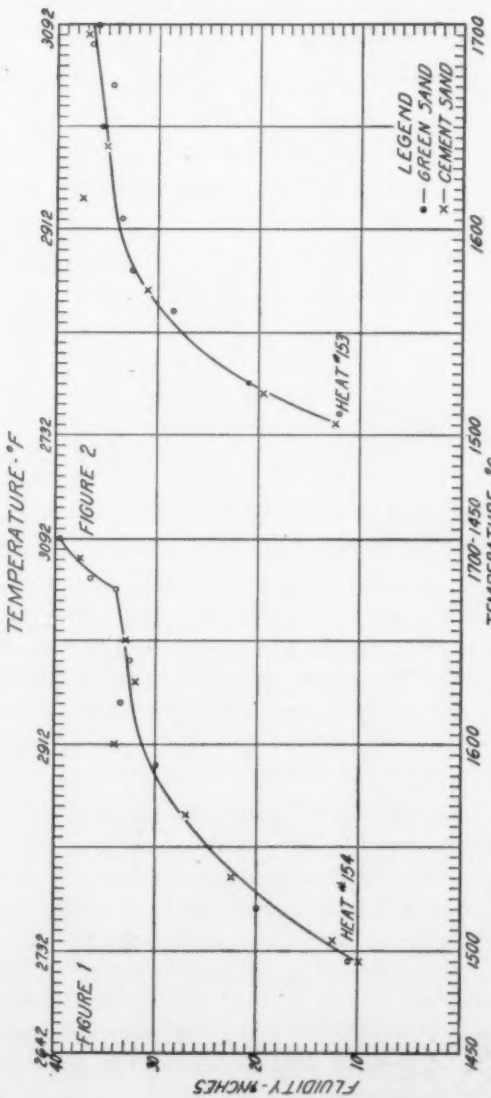


FIG. 87—COMPARATIVE INFLUENCES OF CEMENT AND GREEN-SAND MOLDS ON THE FLUIDITY OF CAST STEEL.

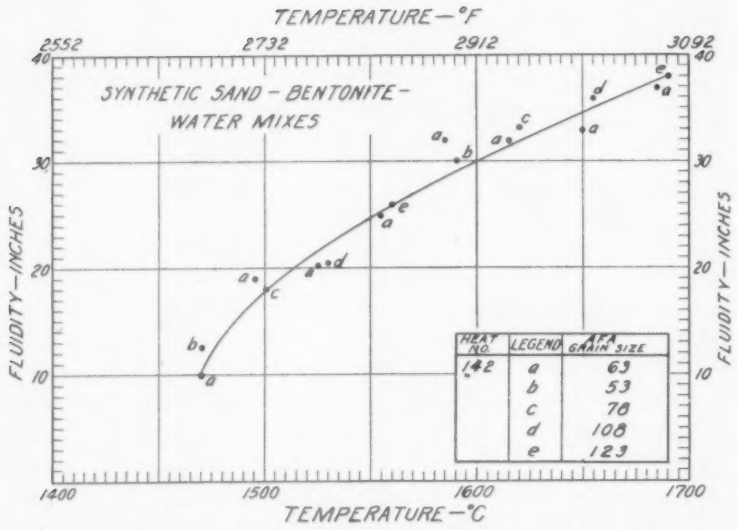


FIG. 38—INFLUENCE OF SAND GRAIN SIZE ON THE FLUIDITY OF CAST STEEL.

result is in accord with the conclusions of Ruff, but not with those of some other investigators.

66. The influence of gases in the mold which might create varying degrees of back pressure as the sand permeability varies with grain size is not considered here, since the spirals were amply vented at the end. This is normal foundry practice and it is clear that abnormal gas pressure against the incoming metal, which would develop in the absence of venting, would cause resistance to its flow and an apparent decrease in fluidity.

67. It is possible that the negligible influence of sand grain size on the running qualities of cast steel can be explained on the basis of the mechanism of flow in a narrow channel. Ruff[3] carried out experiments in which steel was run in a $\frac{3}{16}$-in. flow channel against a heavy layer of paper. As soon as the hot metal reached the paper, a large volume of gas was evolved and the liquid steel was forced backward in the channel against the ferrostatic and inertia pressures. When the test piece was sectioned longitudinally, it was found that a shell of steel had formed in the mold as soon as the metal had run against it and that the liquid steel had run forward and backward through this tube. The wall thickness was surprisingly uniform. It may be mentioned that the thickness and uniformity of this layer at any instant depends on the temperature

and composition of the steel as well as upon the nature of the flow. If conditions were such that the flow was laminar or smooth, the wall thickness would be thinner at a definite temperature than it would be with turbulent flow. The marginal velocity in turbulent flow would be low when the individual particles reached the outside of the flow channel and returned to the interior. Thus more time would be allowed for the transmission of heat to the mold with smooth flow and the resulting shell would build up more rapidly. The marginal velocity in smooth flow is quite high.

68. At any rate, from this elementary discussion of the mechanism of flow, it is evident that a solid wall or stationary zone of metal forms along the flow channel and the remaining liquid steel flows through this tube. Thus any resistance to flow that may be expected as a result of the mold surface being smooth or rough is negligible. This theory will hold only for steel flowing in thin or small sections. In the case of heavy castings, such a large volume of metal is involved that fluidity, as it may be affected by conditions of surface roughness, is of no consequence.

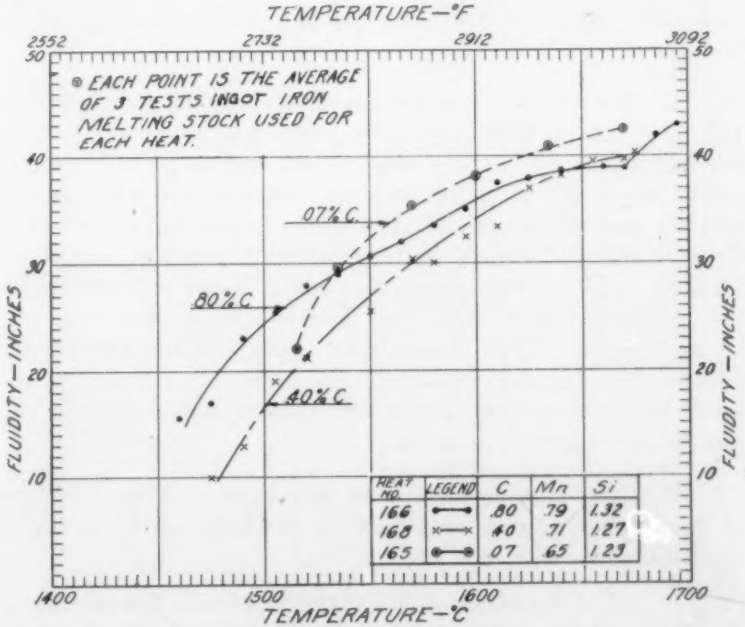


FIG. 39—BASIC INFLUENCE OF CARBON CONTENT ON FLUIDITY OF WELL-KILLED STEELS.

EFFECT OF ALLOYING ELEMENTS ON FLUIDITY

Carbon

69. Carbon content, per se, has but little influence on the fluidity of cast steel. A slight difference in castability apparently does exist, however, if compositions are roughly grouped as low, medium, and high carbon steel. A glance at an equilibrium diagram will show what small gain in fluid life could be expected under ideal conditions from a progressive lowering of solidification temperatures as carbon content increases over the narrow range from zero to about 0.9 per cent, which includes all ordinary steels.

70. To limit variables due to differences in oxygen content, and to determine as far as possible the nature of these variables, three series of these tests were made. Three heats (Fig. 39) were made with approximately 1.25 per cent silicon for the purpose of eliminating the variable of oxidation or at least holding it nearly constant at a low figure. Ingot iron melting stock was used as the base material for each heat to avoid any effect of previous history. The carbon content was adjusted with commercially-pure carbon rod.

71. The effect of carbon on the fluidity of unkilled steels (Fig. 40) was studied using three heats containing very low silicon and manganese. Only enough silicon was added to the higher carbon steels to control the rimming action. Ingot iron was used and the carbon content adjusted with commercially-pure carbon. For the effect of carbon on the fluidity of steels of commercial analysis (0.75 per cent manganese and 0.35 per cent silicon, approximately), bars poured from electric furnace steel were used as melting stock. Three compositions (0.08, 0.30, and 0.60 per cent carbon—Fig. 41) were tested with the degree of oxidation, as governed by silicon content, somewhere between that of unkilled steel and that of high silicon steels.

72. The following conclusions may be drawn from the curves of Figs. 39, 40 and 41 in regard to the influence of carbon on the fluidity of cast steel:

(a) The variation in castability with an increase in carbon content is slight in the high silicon steel (Fig.39) but a definite effect is shown. In unkilled steels (Fig. 40) this in-

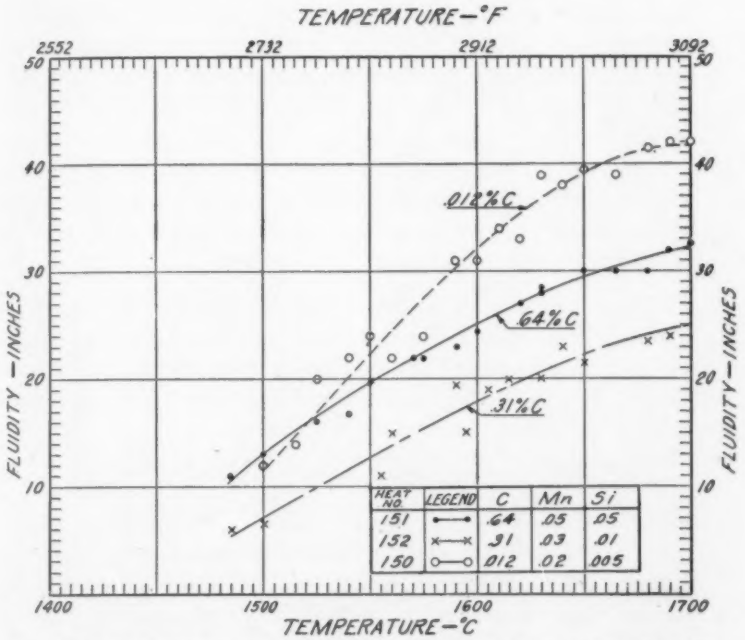


FIG. 40—BASIC INFLUENCE OF CARBON CONTENT ON THE FLUIDITY OF UNKILLED STEEL.

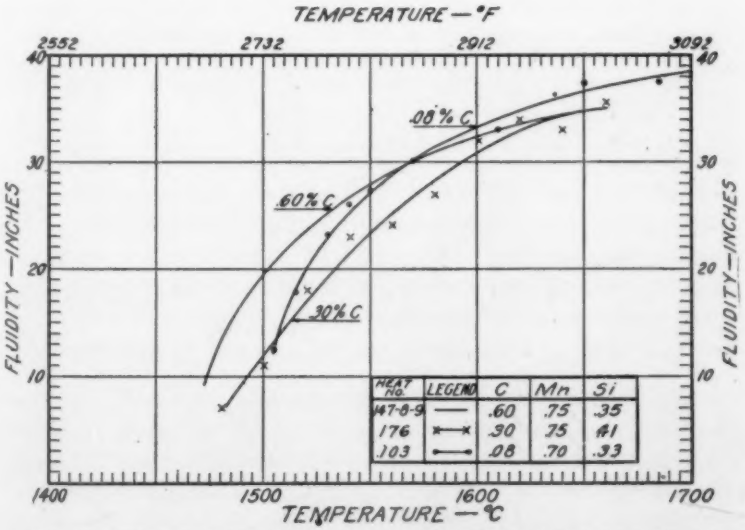


FIG. 41—EFFECT OF CARBON CONTENT ON THE FLUIDITY OF STEELS WITH AVERAGE MANGANESE AND SILICON CONTENTS.

fluence is more marked, but in all cases, especially at temperatures below 1600°C. (2912°F.), fluidity dropped as the carbon was increased from 0.08 per cent or less to 0.30 or 0.40 per cent. An increase in carbon to 0.60 per cent and 0.80 per cent resulted in an increase of fluidity to a value which, at lower temperatures, was greater than for either of the lower concentrations, and intermediate at high temperatures. In other words, fluidity appears to be at a minimum for medium carbon.

(b) The curves for the high silicon steels have the same general form as those for the commercial steels, but the fluidity is higher throughout the range of temperatures investigated. This is undoubtedly due to the high silicon content as shall be shown later.

(c) The fluidity of unkilled steels is markedly lower than the killed steels of the same carbon content.

(d) The fluidity of ingot iron is surprisingly high but is lowered by an increase in carbon. The fluidity of very low carbon steel rises rapidly from its melting point to 1600°C. (2912°F.).

(e) Like many steels, the appearance of ingot iron is no criterion of its fluidity. Visually, it appears extremely dead and sluggish, but in reality it is very fluid.

73. From the results of these tests, it is clear that little practical advantage can be taken of the effect of carbon on fluidity, except perhaps at lower temperatures in well-killed steels.

74. The high fluidity of the ingot iron was particularly surprising since, if fluidity were strictly a function of the iron-carbon diagram, the opposite effect would be expected. The higher liquidus and solidus temperatures, with the resultant lowered degree of superheat at any given temperature, should bring about a decrease in fluidity. That this is not the case can be seen readily.

75. The low fluidity of unkilled steels containing carbon is probably caused by the formation of carbon monoxide which results from the reaction between iron oxide and carbon. The presence of this gas in the flowing stream naturally impedes the progress of the metal by its constant effort to escape. Due to this gas, a comparatively small volume of metal is present per unit

cross-section of flow so that solidification is rapid and fluid life is decreased. Also, flowability is seriously impaired by the increased gas pressure and enhanced turbulence. In steels relatively free from carbon, the carbon-oxygen ratio is so low that the reaction does not proceed rapidly and there is little or no rimming. In order for rimming to take place, both carbon and oxygen must be present in the molten steel. In the absence of either, the steel is normally quiet.

Silicon

76. According to a theory popular in England, the fluidity of a particular alloy should be a minimum if the liquidus-solidus range (the difference between the liquidus and solidus lines) is a maximum. From experimental work done in that country this theory seems to hold for all the usual elements except silicon. In the British work, it was found that, as the silicon content is increased to 1.3 per cent, the fluidity decreases. The liquidus-solidus range also decreases over this range of composition.

77. Results at the Naval Research Laboratory are not in complete agreement with the above. For example, Fig. 1 of Fig. 42 shows a series of fluidity tests made with ingot iron base metal and increasing percentages of silicon. As can be seen, no consistent order exists, the fluidity being markedly increased at 0.57 per cent silicon as compared to 0.34 per cent, and decreasing progressively from this high value to an intermediate value for 0.84 per cent and 1.34 per cent silicon. It seems logical to explain this behaviour on the basis of relative degrees of oxidation and deoxidation, and to ascribe the decreased fluidity at higher concentrations to the inherent influence of the silicon. Alloys with silicon higher than 2.5 per cent were not investigated, since they are of no immediate interest, and hence it is not known how rapidly fluidity may increase with higher silicon. The results on silicon further strengthen the argument against fluidity predictions based on the equilibrium diagrams.

78. The data on the effect of silicon were confirmed by a check heat (Fig. 2 of Fig. 42); the temperature was held constant and the alloying element was added by increments, three spirals being poured after each addition. The slight drop in fluidity noted for point number 1 is the result of silicon having dropped from 0.43 per cent to 0.35 per cent as the result of stirring the slag-free

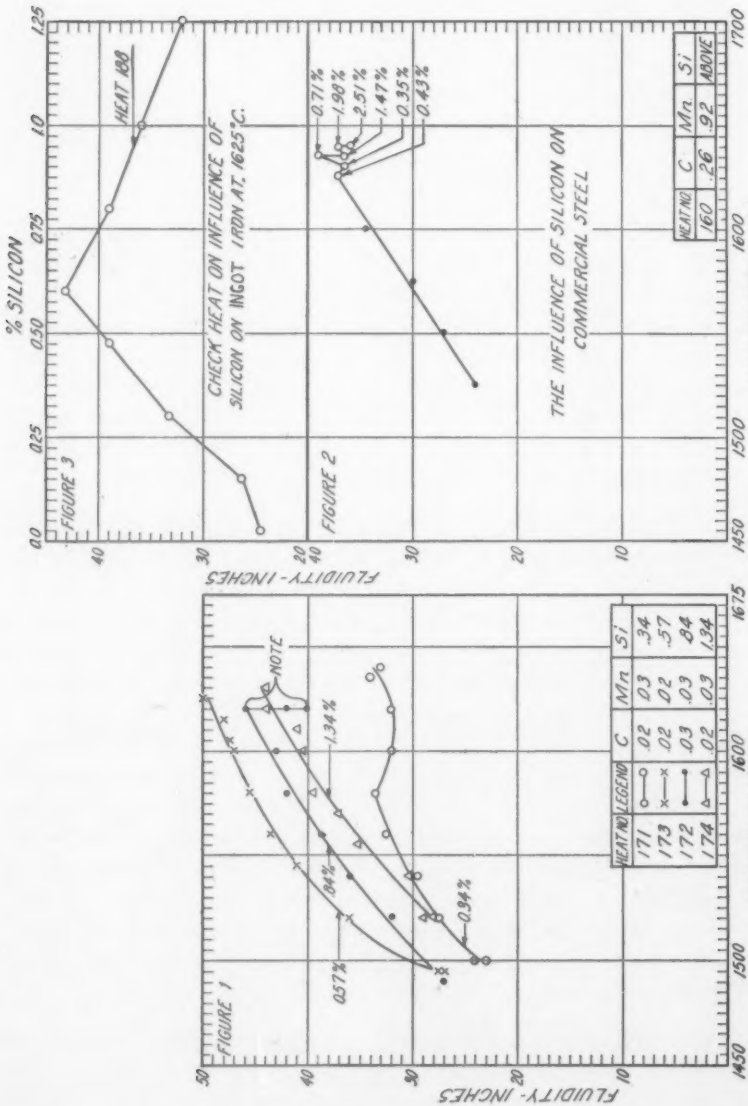


FIG. 42—INFLUENCE OF SILICON ON THE FLUIDITY OF INGOT IRON.

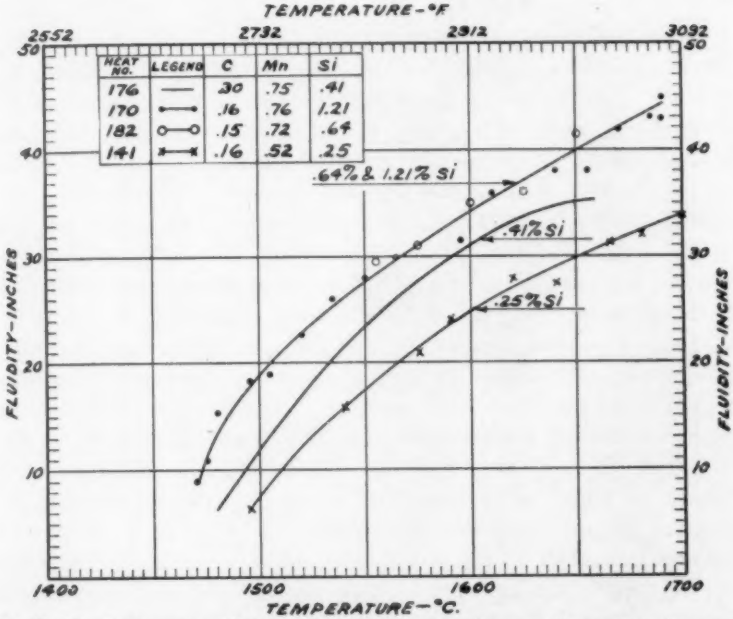


FIG. 43—THE INFLUENCE OF SILICON ON THE FLUIDITY OF STEELS OF COMMERCIAL ANALYSES.

bath in air. The fluidity was restored and slightly increased by raising the silicon to 0.71 per cent. The fluidity was lowered by 1.47 per cent silicon to a level which was not greatly changed by further additions to 2.51 per cent. From Fig. 43, it may be seen that in steels of commercial analyses containing normal percentages of carbon, no change in fluidity was found as the silicon was increased from 0.64 per cent to 1.21 per cent. However, marked increases in fluidity were observed as the silicon was increased from 0.25 to 0.41 per cent and from 0.41 to 0.64 per cent.

79. The decreased fluidity with increases in silicon concentration from 1 to 2½ per cent was surprising, since steels containing 2 per cent or more of this element are well known for their tendency to run into thin cracks in molds, forming fins. Sims and Lorig have pointed out, in private correspondence, the apparently excellent fluidity of high silicon steels and especially of transformer steels containing about 4 per cent silicon. More work will be done to determine why this characteristic does not show up in the test results presented in this paper. The peculiar behaviour in the tests made with ingot iron cannot be clearly explained on the basis of results so far obtained and it is planned to continue this work.

Iron Oxide

80. The peculiar dip in the 0.34 per cent silicon curve in the region of 1580°C. (2876°F.) and the 0.84 per cent silicon curve at 1620°C. (2948°F.) (Fig. 42) is the result of the loss of silicon by exposure to the atmosphere at elevated temperatures. This can be more clearly explained by a consideration of Fig. 44. As the temperature of steel is raised in the absence of a protective slag, a point is reached where oxidizable elements are seriously attacked by the oxygen of the air. At lower cast steel temperatures, the relative deoxidizing powers of silicon, manganese, and carbon are in the order named. However, at higher temperatures, this order is reversed; carbon is most effective and the order becomes carbon, manganese, and silicon. It may be mentioned here that Sims concluded from extensive work on deoxidizers for cast steel that for standard melting practice and normal concentration of iron oxide, 0.35 per cent silicon is sufficient for satisfactory deoxidation at normal pouring temperatures. As molten steel cools toward solidification, silicon becomes increasingly effective as a deoxidizer. Chemical analysis of the spirals showed that the silicon of curve *A*, Fig. 44, was lost very rapidly as the temperature exceeded 1580°C. (2876°F.), thus accounting for the serious drop in fluidity. It was found that by the time the temperature had been raised

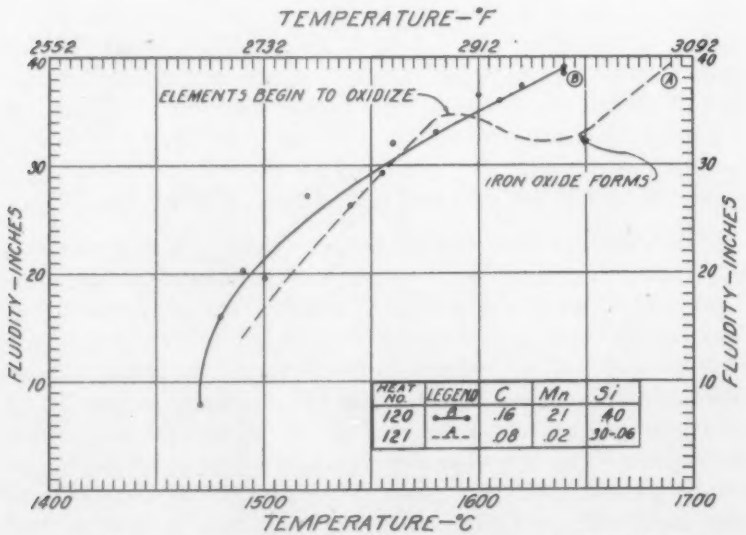


FIG. 44.—THE TREND OF FLUIDITY AS A FUNCTION OF THE DEGREE OF OXIDATION.

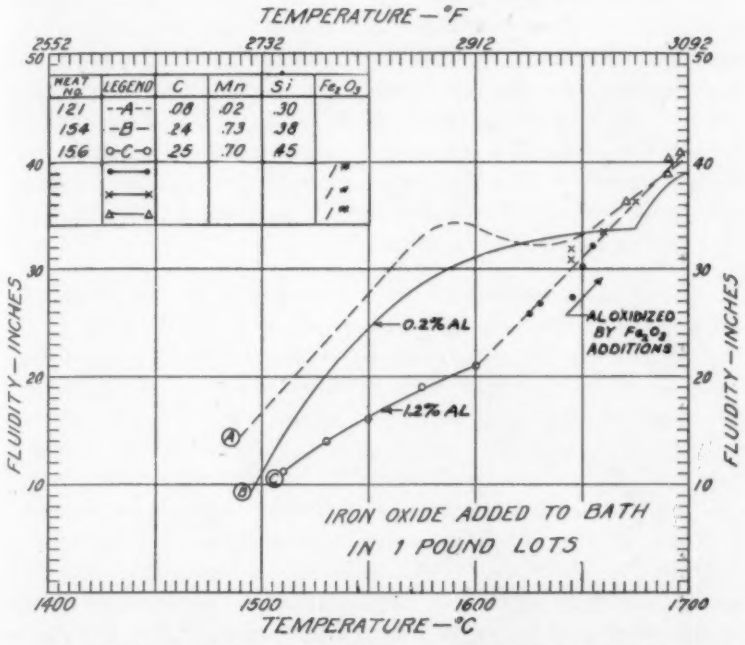


FIG. 45—THE INFLUENCE OF IRON OXIDE ON THE FLUIDITY OF CAST STEEL CONTAINING A LARGE EXCESS OF DEOXIDIZER.

to 1650°C. (3002°F.), the silicon had dropped to 0.06 per cent, although it had been 0.30 per cent at the beginning. At this point, instead of a continued fall in fluidity there was an unexpected increase as the temperature was further raised to 1690°C. (3074°F.). The same thing was noted in other heats as shown by several curves throughout the report. This phenomenon is hard to account for, unless it is the result of an increasing iron oxide concentration. To check this possibility, the oxide content was raised by adding iron ore. Two series of four spirals and one series of five spirals were poured after each successive addition as shown in Fig. 45. The heat of steel chosen for the experiment was one of the aluminum series. The first five spirals were poured at increasing temperatures to establish the curve for 1.2 per cent aluminum. From preceding work on 0.2 per cent and 0.6 per cent aluminum steels, it was apparent that the 1.2 per cent aluminum steels were likely to have extremely low castability. Thus, if iron oxide were effective in restoring fluidity lost by excessive deoxidation, it would be demonstrated clearly in a heat of this type. Curves *A* and *B* of Fig. 45 are typical curves which show a sudden increase in fluid-

ity at elevated temperatures, the spirals approaching a common length. From curve *C* of Fig. 45, it is seen that the fluidity of the very sluggish aluminum steel was increased by iron oxide to the same degree as for steels in which the iron oxide had been allowed to build up by stirring the slag-free bath in air. From the behaviour of the unkilled steels of the carbon series discussed previously, it is evident that beyond a certain threshold value, a further increase in iron oxide would definitely decrease fluidity as measured by the spiral fluidity mold.

81. A comparison between a steel low in initial silicon content and one correspondingly higher melted under the same conditions, is given in Fig. 41. These curves show that, if silicon drops below a critical value, there is increased danger from oxidation. This does not mean that many low silicon steels are not satisfactorily poured every day, but it does mean that, unless properly protected, such steels may be unduly sensitive to conditions of handling. This fact is further supported by the 0.34 per cent silicon curve of Fig. 42. High initial silicon is not a guarantee of good fluidity under all conditions, as shown previously, nor is it positive insurance against excessive oxidation. In spite of an initial silicon of 0.84 per cent in one of the curves of Fig. 42, silicon was lost and the fluidity was lowered by stirring the slag-free steel

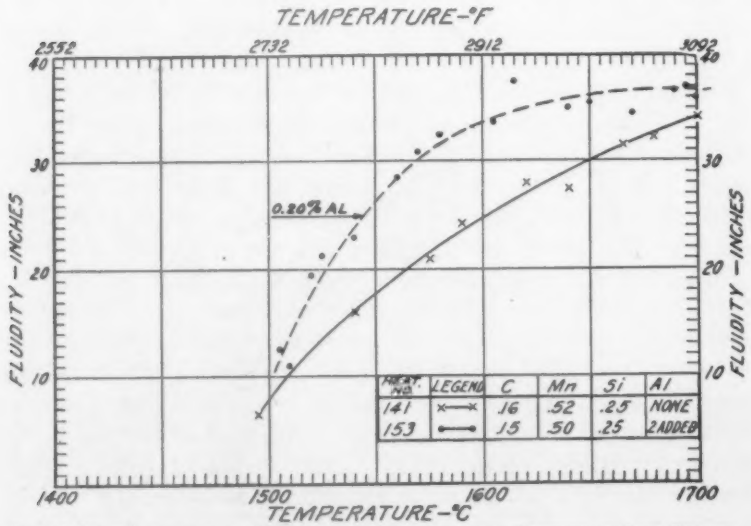


FIG. 46.—THE INFLUENCE OF ALUMINUM IN INCREASING THE FLUIDITY OF LOW SILICON CAST STEEL.

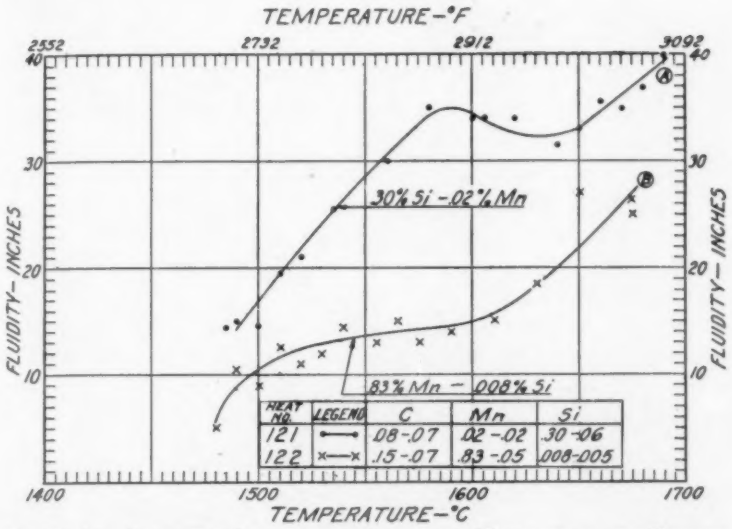


FIG. 47—THE COMPARATIVE INFLUENCES OF SILICON AND MANGANESE ON THE FLUIDITY OF CAST STEEL.

for a period of 5 min. at 1620°C. (2948°F.). These conditions were more severe than those discussed above, however. It does not follow that low-silicon steels always lose silicon. It is to be emphasized that such compositions are more susceptible to adverse conditions than are higher silicon steels.

82. That fluidity is directly affected by the degree of oxidation of the steel seems evident from Fig. 46. The low fluidity of steel 141 can be attributed to the low silicon content and a consequently lower degree of deoxidation. When a steel of similar silicon content is deoxidized with aluminum (heat 153), the fluidity is greatly increased and the susceptibility to undue oxidation is diminished. Figure 43 gives a further comparison between a low silicon steel and one containing slightly more silicon. The increase in fluidity with the higher silicon is definite throughout the temperature range. Referring to Fig. 43, it is seen that in steels of commercial analysis, an increase in silicon from 0.41 to 0.64 per cent is of benefit from the standpoint of decidedly increased fluidity. However, nothing is gained by further additions up to 1.25 per cent which may, as shown in Fig. 42, bring about a decrease in flowability. It is believed that silicon can be even higher than 0.6 per cent without seriously impairing casting quality.

83. It may be of interest at this point to consider the com-

parative effect of silicon and of manganese upon the fluidity of cast steel. Figure 47 shows two curves which clearly indicate the effect of these elements individually in determining the fluid character of cast steel. Curve *A* is of a manganese-free steel containing initially 0.30 per cent silicon, while curve *B* represents a silicon-free steel containing at the outset 0.83 per cent manganese (the steels have about the same carbon content). From the results of these tests, it is evident that silicon, if maintained at a high enough level, may greatly improve fluidity, while manganese in usual amounts does not. Many times during regular fluidity heats, 0.45 per cent or more manganese in excess of that already present, was added at some point near the end of the heat to further check its effect. Spirals poured immediately before the addition and immediately after showed no difference whatever.

84. When fluidity tests were made at the arc furnace for routine determination of the proper tapping time, spirals poured before and after final manganese additions had the same lengths, whereas after the final silicon additions the length of the spirals often increased as much as 32 per cent. Manganese has its greatest influence on fluidity at the lower temperatures, and such tests as those above serve only to indicate the small effect of the element at higher temperatures. The effect of manganese on fluidity is discussed in the following paragraphs.

Manganese

85. Manganese, when present in high concentration, increases fluidity markedly in the lower temperature range and the curves tend to be much flatter than those representing ordinary steels. Figures 1 and 2 of Fig. 48 present the results of work done so far. Curve *B* is typical of a normal plain carbon steel and curve *A* is for high manganese. It is well known that Hadfield steel is very fluid at low temperatures and the present data add further evidence. Curves *A* and *B* for the 0.75 per cent and the 13.6 per cent manganese steels coincide and cross in the region of 1600°C. (2912°F.). Above this temperature, the higher manganese steel actually becomes inferior in fluidity to the 0.75 per cent manganese steel.

86. Because of the basic nature of this class of steels, it is difficult to manufacture them in an acid lined crucible. To maintain a quartz protected thermocouple in the bath for accurate temperature measurement is decidedly troublesome. No protection

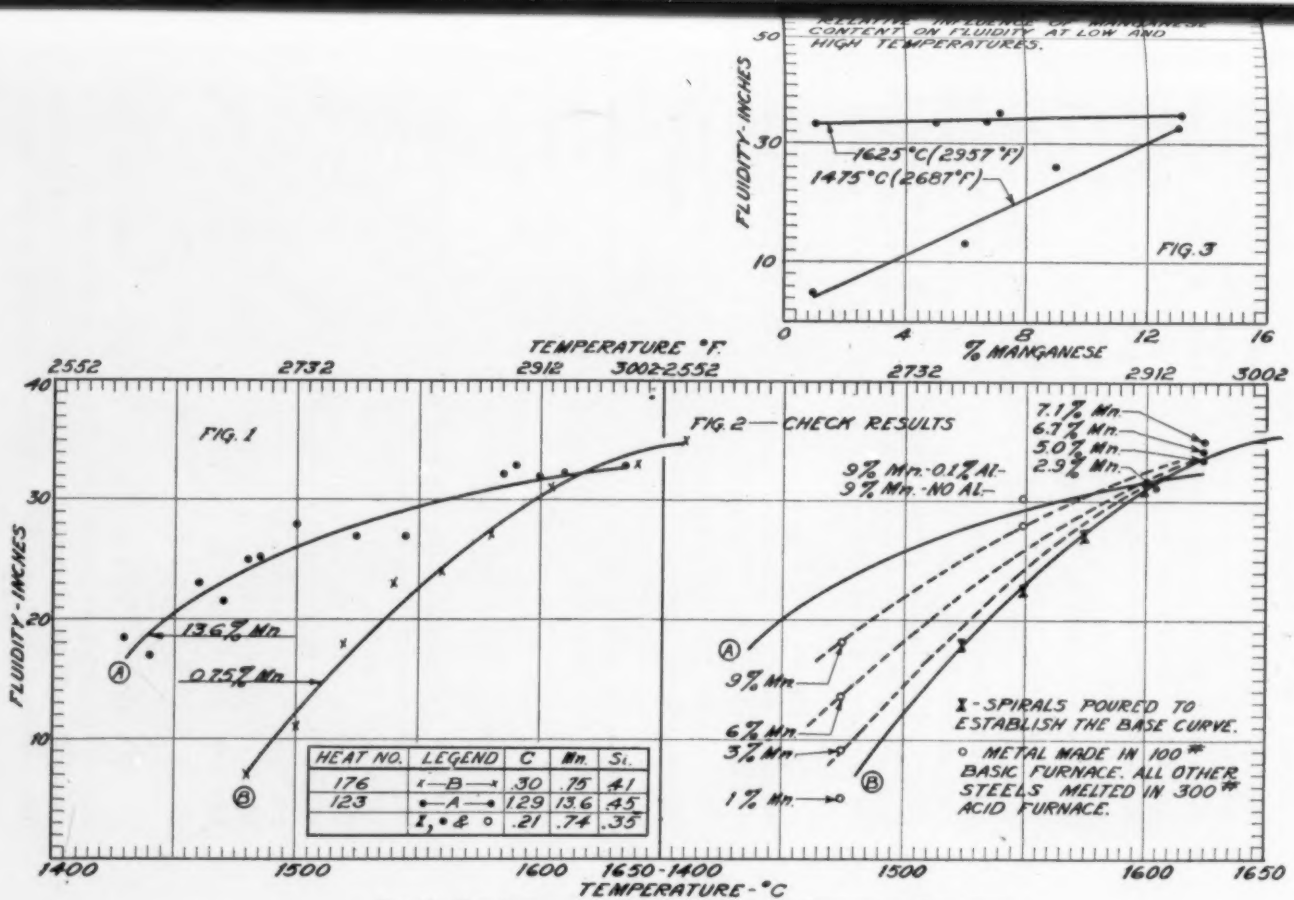


FIG. 48—THE INFLUENCE OF MANGANESE ON THE FLUIDITY OF CAST STEEL.

tubes of basic refractory are available which will withstand steel temperatures and, since a quartz tube cannot be used with basic practice if it comes in contact with the slag, a more complete study of the influence of manganese was not made. However, sufficient information is provided by these curves to furnish a practical explanation of the behaviour of high manganese steels. It is also clear from this work, supplemented by practical foundry results, that in larger castings, the satisfactory pouring temperature for this steel lies between 1450°C. (2642°F.) and 1500°C. (2732°F.). There is little advantage, from the standpoint of fluidity, in increasing the temperature much beyond this limit and porous and bad castings may result if this is done. John Howe Hall, however, has pointed out by private correspondence, that high temperatures can be advantageously used for pouring light castings if suitable sands are employed. He states that 1600°C. (2912°F.) is not too high.

87. Figure 2 of Fig. 48 shows the results of tests made to check the previous individual heats of Figure 1. It may be seen that at 1625°C. (2957°F.) the curves for manganese contents from 2.9 to 7.1 per cent are practically coincident. The points used in establishing the base curve check heat number 176 satisfactorily and indicate the accuracy of the technique. Each of the check points is an average of four spirals and the maximum variation was less than one inch. The metal, up to the time of the first manganese addition, was practically the same as that of the standard curve of heat 176, and the variation in carbon is too small to be of consequence from the standpoint of fluidity.

88. To determine the effect of manganese at lower temperatures for concentrations between the extremes of curves *A* and *B*, (Fig. 2, of Fig. 48), a check heat was made in a basic lined induction furnace. The thermocouple was protected with a thin walled quartz sheath instead of the double protection tube used for the acid heats. The slag was kept away from the center of the bath where the thermocouple was inserted only long enough to come to temperature. As long as the basic slag is kept away from the quartz, erosion of the protecting tube is comparatively slow.

89. As shown in Fig. 2 of Fig. 48 (points marked by round circles) the temperature of the bath was maintained at 1500°C. (2732°F.) and spirals were poured with the compositions indicated. The results show clearly how fluidity is affected at this tempera-

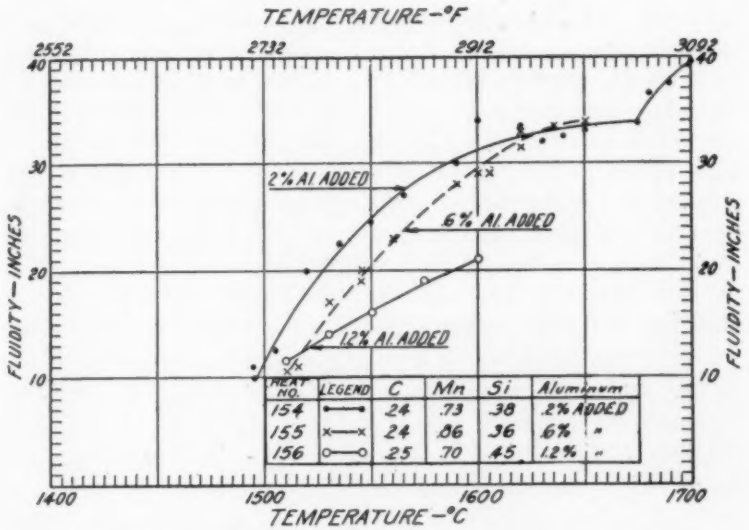


FIG. 49—THE INFLUENCE OF LADLE ADDITIONS OF ALUMINUM ON THE FLUIDITY OF CAST STEEL.

ture by increasing the manganese content only, and are in good agreement with the data previously obtained.

90. To determine the influence of aluminum on high manganese (9 per cent) steel at higher temperatures, the bath was raised to 1550°C. (2822°F.) and a spiral poured. Next 0.10 per cent aluminum was stirred into the bath and another spiral immediately poured. As can be seen, an increase of 2-in. resulted, which is a substantial amount at this temperature.

Aluminum

91. In the discussion of the silicon series, it was shown that the fluidity of cast steel was improved by the addition of a small amount of aluminum when insufficient silicon was present to accomplish the desired degree of deoxidation. As just shown in the manganese series, a slightly increased fluidity was obtained by adding aluminum to a high manganese steel. The amount added in the latter case was small and further work will be necessary to determine how greater amounts affect the fluidity of Hadfield steel.

92. Figure 49 shows that, while aluminum may improve fluidity when added in proper amounts, too much aluminum has

an adverse effect. It appears probable that its chief value, from the standpoint of fluidity, lies in its deoxidizing power. Too much or too little oxygen, present either as such or as an oxide of iron, is clearly detrimental to fluidity, but it appears that a critical amount is essential. This lends a semblance of truth to the long held differentiation between the relative casting qualities of over-reduced and under-reduced steels. When aluminum or some other deoxidizer is added in proper proportions, it appears possible to obtain maximum fluidity. It is probable that the decreased fluidity which results from increased aluminum concentration is due to the tendency of the molten metal to form tough aluminum oxide films.

93. The curves for the 0.2 and 0.6 per cent aluminum steels of Fig. 49 become coincident in the region of 1625°C. (2957°F.) because the low aluminum heat lost both aluminum and silicon by oxidation. If the spirals had been poured on decreasing temperatures and a protective slag could have been maintained at all times, it is certain that the curves would have continued nearly parallel throughout their entire range.

Copper

94. The influence of copper on the fluidity of cast steel is shown in Fig. 50. The curves indicate the progressive increase in fluidity brought about by increases in the copper concentration to 3.7 per cent. Check tests made at constant temperature, vary-

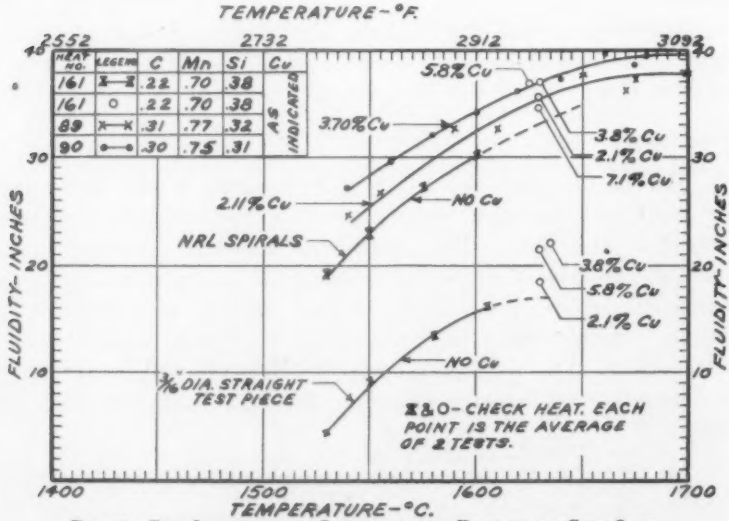


FIG. 50—THE INFLUENCE OF COPPER ON THE FLUIDITY OF CAST STEEL.

ing only the amount of copper, verified the original curves. Not only does the same order of spiral increase prevail as the copper content is raised, but the same lengths were obtained by both methods of testing. Increasing the copper from roughly 4 to 6 per cent showed no beneficial influence on spiral length and 7 per cent copper actually decreased the length of flow. The results obtained by use of the Ruff $\frac{3}{16}$-in. diameter flow channel confirmed those obtained from the spiral and, surprisingly enough, the increases in length were of the same magnitude.

Nickel

95. The effect of nickel (1.4 to 5.1 per cent) on the fluidity of a steel with normal silicon, manganese, and carbon is shown in Fig. 51. The series of curves at the left of Fig. 51 show that fluidity increased in proportion to the nickel concentration to 3.25 per cent. However, it decreased with higher nickel, as shown by the series of curves on the right in Fig. 51.

96. The steeply rising portion of the curve between 1450 and 1500°C (2642 and 2732°F.) and the straight line portion at higher temperatures are characteristic of these steels. The fluidity of nickel steels seems to be a linear function of temperature after the initial knee is reached, while in most steels at elevated temperatures the increase in length of flow per degree rise of temperature gradually drops off. Also, plain carbon steels, as well as most of the others which were tested, show a more gradual initial increase.

97. By referring to the iron-nickel equilibrium diagram (Fig. 52) it is seen that the solidus decreases rapidly from 1530°C. (2786°F.) with no nickel to 1495°C. (2723°F.) at 3.25 per cent. From this concentration up to 10 per cent, there is no change in the temperature of the solidus. In the nickel steels, the decreasing solidus temperature may account for the increased length of flow by raising the degree of super-heat at a given temperature, since the state of deoxidation and other variables were not influenced by the nickel concentration. It has been explained that, while the solidus cannot be taken as a true indication of the fluidity of steels in general, any change in the solidus will, in certain cases such as the present, govern the temperature at which the critical amount of solidified crystals forms and stops flow. In the region from 3.25 to 10 per cent nickel, the thermal range above the solidus is

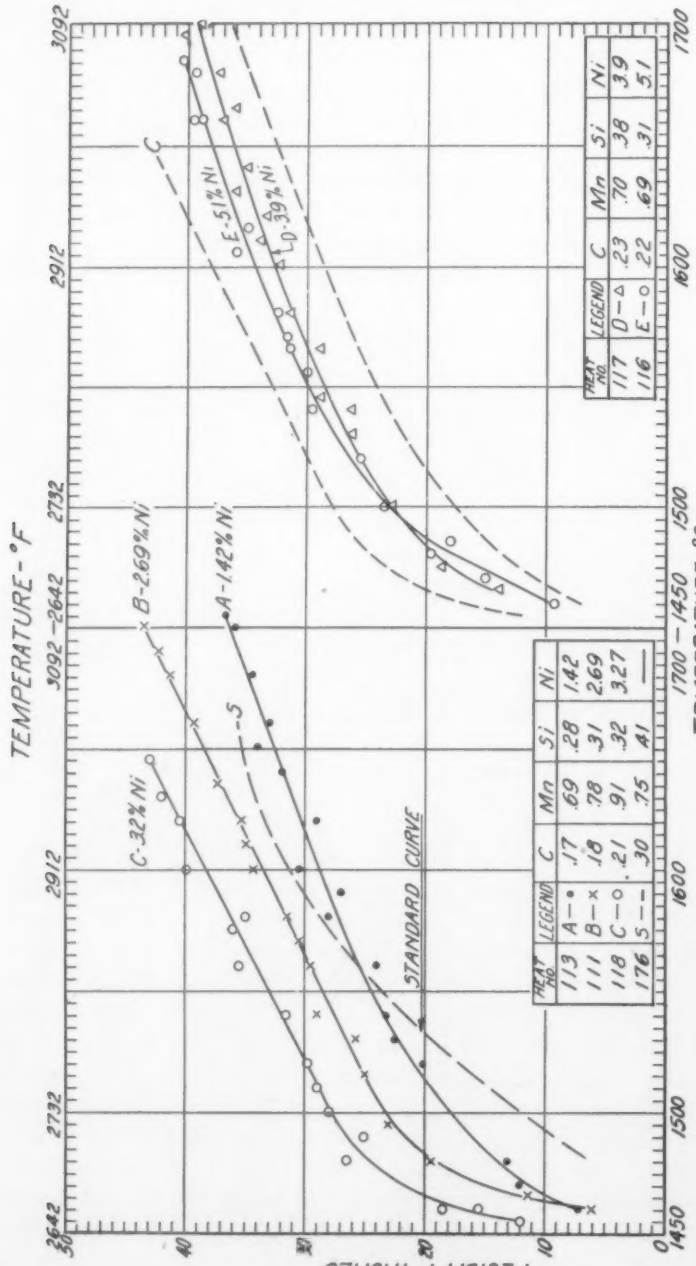
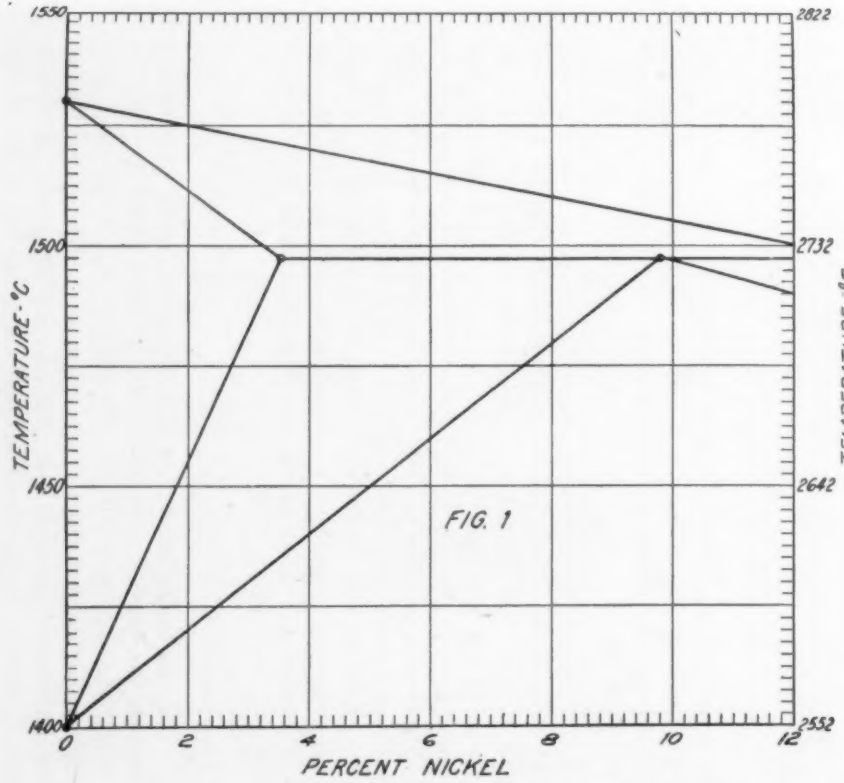

TEMPERATURE - °F
TEMPERATURE - °C
FLUIDITY - INCHES
C-.32% Ni
B-2.69% Ni
A-1.42% Ni
STANDARD CURVE
E-.51% Ni
D-.39% Ni
C
HEAT NO | LEGEND | C | Mn | Si | Ni
113 | A—• | .17 | .69 | .28 | 1.42
111 | B—× | .18 | .78 | .31 | 2.69
118 | C—○ | .21 | .91 | .32 | 3.27
176 | S— — | .30 | .75 | .41 | —
HEAT NO | LEGEND | C | Mn | Si | Ni
117 | D—△ | .23 | .70 | .38 | .39
116 | E—○ | .22 | .69 | .31 | .51

FIG. 51—THE INFLUENCE OF NICKEL ON THE FLUIDITY OF CAST STEEL.



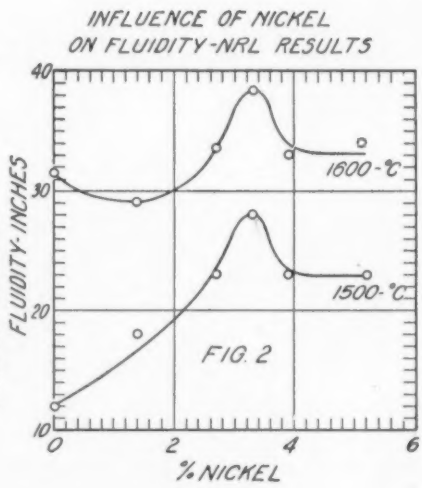


FIG. 52—THE PERITECTIC REGION OF THE IRON-NICKEL DIAGRAM*.

* "ALLOYS OF IRON AND NICKEL," Alloys of Iron Monograph, vol. 1, p. 27.

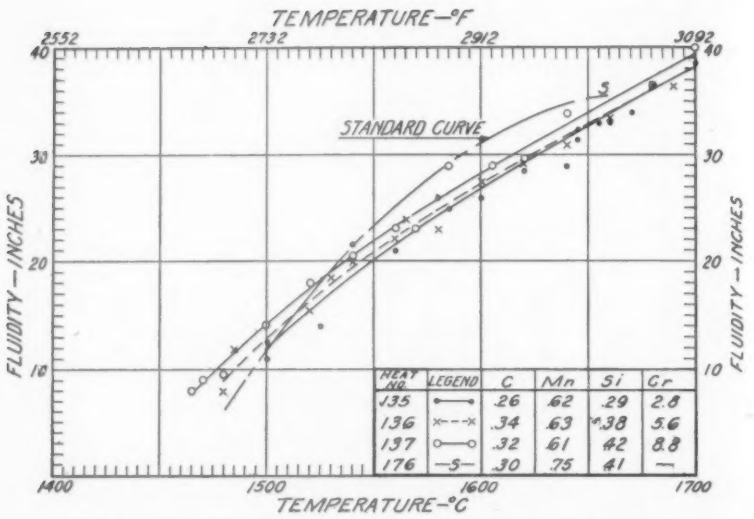


FIG. 53—THE INFLUENCE OF CHROMIUM ON THE FLUIDITY OF CAST STEELS.

the same for any chosen temperature and the decreased fluidity for these compositions is undoubtedly an inherent property of the nickel itself. Extremely high nickel alloys do not possess especially good fluid life.

98. Figure 2 of Fig. 52 shows the trend of fluidity of the nickel steels as a function of alloy concentration at 1500 and 1600°C. (2732 and 2912°F.). These curves are derived from those of Fig. 51 and are much alike. While at 1500°C., fluidity steadily increases in proportion to the nickel concentration from zero to 3.25 per cent, at 1600°C., the length of flow decreases and then increases beyond 1.42 per cent. The curve for the plain carbon steel, curve *S*, Fig. 1 of Fig. 51, starts at a lower value but rises more steeply to a maximum than the 1.42 per cent nickel steel. This accounts for the difference in the iron-rich end of the curves of Fig. 2 of Fig. 52.

Chromium

99. As can be seen from Fig. 53, the influence of increasing amounts of chromium on the fluidity of steel is not marked. At normal pouring temperatures, the fluidity of 2.8 per cent chromium is slightly less than plain carbon steel. By further increasing the chromium content to 5.6 and 8.8 per cent, no further definite change in the shape or position of the curve was found.

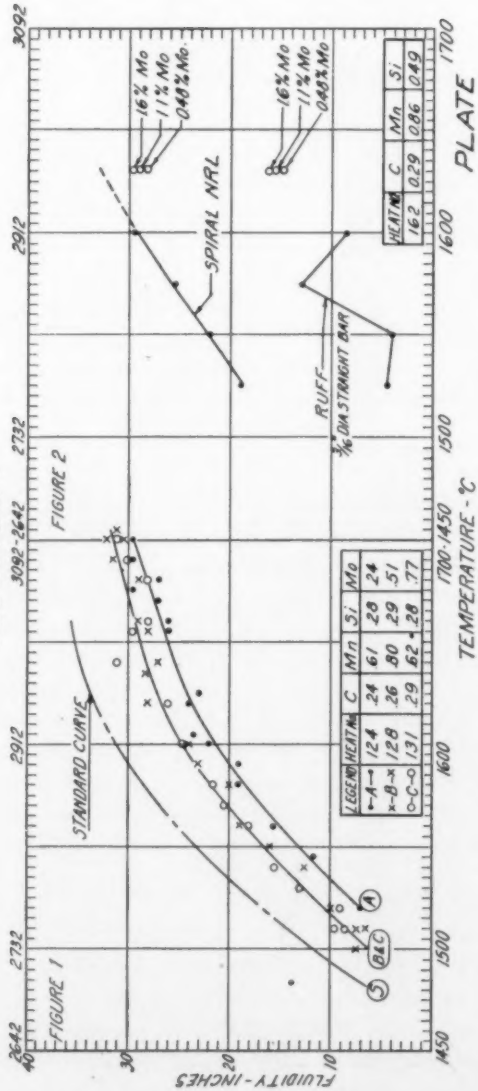


FIG. 54—THE INFLUENCE OF MOLYBDENUM ON THE FLUIDITY OF CAST STEEL.

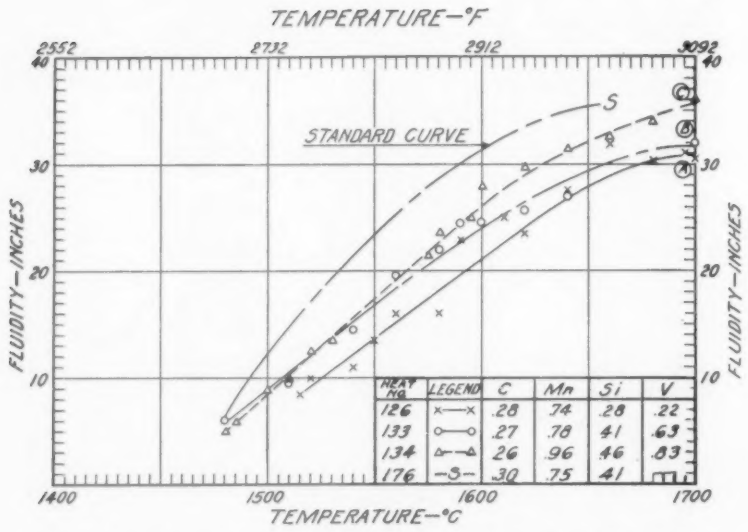


FIG. 55—THE INFLUENCE OF VANADIUM ON THE FLUIDITY OF CAST STEEL.

There is a very slight increase in fluidity at all temperatures for the melts higher in chromium. This is probably due to a slightly lowered solidus temperature resulting from the increased chromium. A characteristic of steels containing chromium is a nearly straight line curve. This indicates that, in some alloys, fluidity may be directly proportional to the temperature, except near the freezing range. These results are in good agreement with those of British investigators who found that there was a sudden drop in fluidity for the initial 1.1 per cent chromium and only a small improvement for further increases to 7.5 per cent. Their investigation included percentages from 1.1 to 25.0 per cent in seven steps and showed a steady small increase in spiral length up to 25 per cent.

Molybdenum

100. Because of the importance of molybdenum as an alloying element in steel castings, its effect on fluidity was studied by adding 0.24, 0.51, and 0.77 per cent to plain carbon steel. The amount of molybdenum usually needed is seldom more than 0.75 per cent so this was taken as the upper limit for the investigation. Molybdenum, like chromium and vanadium, decreases fluidity somewhat, even when so small an amount as 0.24 per cent is added (curve *A* of Fig. 54). As the amount is increased, the fluidity is

slightly improved and a single curve (marked *B* and *C*) serves for both 0.51 and 0.77 per cent molybdenum. At no concentration tested did the fluidity quite equal the standard curve for steel containing no molybdenum.

101. While molybdenum decreases fluidity in the same way as large percentages of chromium, the curves for steels containing molybdenum are not straight, like those for chromium steels, but are curved like those for carbon steels.

102. Figure 2 of Fig. 54 presents the results of a check heat which employed the usual technique and satisfactorily verified the results of Fig. 1 of Fig. 54. Each point is the average of two tests poured in rapid succession. In these tests, the molybdenum was 0.48, 1.1, and 1.6 per cent, and very little difference was noted in fluidity, except for the initial decrease. Results using the Ruff test piece showed a similar trend.

Vanadium

103. Figure 55 shows the fluidity tests on steel containing 0.22, 0.27, 0.63, and 0.83 per cent vanadium. The amount normally used in plain carbon steel for castings is well under 0.25 per cent.

104. Curve *A* of Fig. 55, when compared with the standard curve *S*, without vanadium, shows a definite drop in flowability brought about by the 0.25 per cent vanadium. Further additions, up to 0.83 per cent, increase fluidity to the extent shown by curves *B* and *C* but the maximum fluidity does not equal that of the vanadium-free steel. The family of curves representing these steels exhibits a knee or dropping off at elevated temperatures.

Copper-Silicon-Manganese Steel

105. Among the special fluidity tests which were made, was one of a commercial steel for which very high flowability was claimed. This steel contains roughly 1.75 per cent copper, 1.25 per cent silicon, 1.0 per cent manganese, and 0.20 per cent carbon. This alloy is used for pouring castings with long thin members which are difficult to cast with ordinary steel.

106. The extent to which flowability is increased over a plain carbon steel is evident from a comparison of curves *A* and *S* of Fig. 56, and it may be seen that the claims regarding castability are well founded, since the steel was very fluid throughout the en-

tire range of temperatures used for the test. The enhanced fluidity is undoubtedly due to the combined influence of the high silicon and copper. The silicon probably exerts the greater benefit, since it has been shown to have a marked influence up to or above 0.60 per cent in ordinary carbon steels. A noticeable improvement in a 2 per cent copper steel was also found. Fig. 4 presents the results of work on fluidity done at Battelle Memorial Institute and several copper bearing steels were included in the investigation. In these tests, compositions approximating the analysis indicated above had superior characteristics.

Nickel-Silicon Steel

107. To determine whether combinations of elements have an additive beneficial influence on fluidity, a heat was made using those proportions of nickel and silicon which, when tested individually, gave the longest lengths of spiral. It had been found that 0.60 to 1.25 per cent silicon gave maximum flowability and that the critical amount of nickel was about 3.25 per cent. Thus, if these proportions were used and the effect of the elements were cumulative, an extremely fluid composition should result.

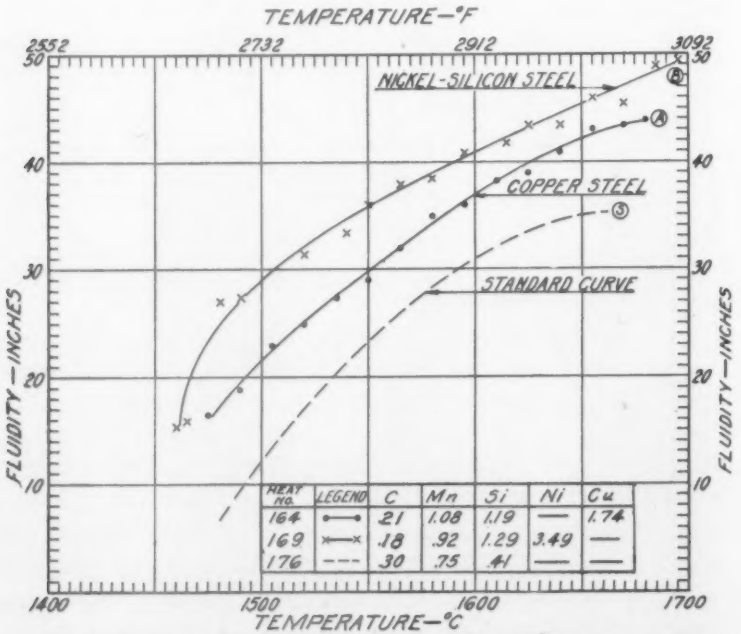


FIG. 56—FLUIDITY OF SPECIAL STEELS ALLOYED TO GIVE MAXIMUM CASTABILITY.

108. It was gratifying to find that this particular steel (*B* of Fig. 56) proved to have the best fluid life of any composition ever tested at the Naval Research Laboratory. The shape of the curve shows predominantly the influence of the nickel concentration by the rapid rise at lower temperatures and its later change into a straight line which maintains a steady rise even at 1700°C. (3092°F.). That silicon has played its part in improving the fluidity, is shown by comparing curve *B*, Fig. 56, with curve *C* of Fig. 1 of Fig. 51, which contain respectively 1.25 and 0.32 per cent silicon with very nearly equal amounts of nickel. The steel with the higher silicon shows an increase of approximately 3-in. in spiral length at temperatures above 1525°C. (2777°F.). Below this temperature, the curves are coincident. The results of these investigations not only show the value of this method of fluidity testing as a laboratory tool for obtaining fundamental information but also shows the adaptability of the technique to the solution of practical foundry problems.

GENERAL DISCUSSION

Dependence of Length of Test Casting on Rate of Flow

109. It might be expected that the length of spiral would depend directly upon the rate of entry of the steel into the flow channel. Inertia head, due to an increased velocity of the metal stream, seemingly should result in greater lengths of flow. Ruff found, however, that when the velocity of steel flowing in a 5 mm. channel was increased from 100 to 200 mm. per sec., there was no appreciable change in the measured fluidity, but that a higher velocity actually decreased the length of flow. Similar results were found in the current test work when extreme differences in rates of pouring were used. Only qualitative indications were obtained, but it was rather surprising to find that very fast rates of pouring gave shorter spirals. Ruff suggested that this unexpected behavior might be explained on the basis of an increase in the internal friction of the flowing mass as the rate of flow increased above a critical value.

Influence of Casting Temperature

110. The influence of casting temperature on the length of flow is as surprising as the effect of the rate of pouring. Contrary to generally published information, increases in casting tempera-

ture above a certain value result in smaller increases in fluidity. That is, for any given increment of temperature above the break in the temperature-fluidity curves, the corresponding increase in casting length becomes less and less. This is clearly indicated by the characteristic knee shown in most of the curves of this paper. Thus it becomes evident that fluidity-temperature curves which show fluidity increasing toward infinity are incorrect. The sharp initial rise in the fluidity of nickel steels with increasing temperature, as compared to the very steady rise of the chromium steels, is an extreme illustration. The lengths of flow for the chromium steels show no selective influence of high or low temperatures. In the plain carbon steels, the slopes of the curves are continually changing above the initial knee, indicating a progressively decreasing influence of elevated temperatures on fluid life.

111. The behavior of steels in this respect is no doubt a result of internal conditions in the flowing stream. An increasing tendency for turbulence at elevated temperatures probably causes an accelerated cooling of the stationary wall zones, as explained above, and slightly lessens the maximum benefit of temperature.

112. Dynamic laws limit the flowability of a metal by the rapid increase in the resistence to flow which results when maximum initial velocities are exceeded. Likewise, thermal laws limit running capacity by making it impossible for the end velocities of flow to drop below the value governed by solidification of the flowing mass. Thus any evaluation of fluid life must be obtained between these two limiting states.

113. A large photograph of a typical spiral is shown in Fig. 30. It may be noted that an incompletely filled central portion exists between the initial and final well-filled sections. The statement of a few principles may serve to clarify the flow conditions existing in such a test piece.

114. If a moving mass of molten steel is watched closely, films can be seen continually forming, breaking, and reforming over the entire surface. If flow in the small fluidity channel be considered, it is clear from the character of the rippled surface portion that films are continually forming and breaking at the leading tip, or pilot head, of the flowing stream. These films are always acting to slow down the metal stream and bring it to rest, but only when the velocity head of the metal behind and the tem-

perature of the metal ahead have decreased to the critical value where the films are strong enough to do so. The existence of these films is manifested in many ways.

115. At the entrance to the spiral, the metal is at its maximum temperature and the effect of surface films is at a minimum. Those films which do form are immediately washed away by the hotter metal and by the greater volume of metal which flows past a given point in this region and heats up the sand. In this portion, and for a distance along the spiral which was found to be influenced by the temperature of the metal, the mold cavity is faithfully reproduced with no ripples or surface imperfections. Farther along the spiral, the temperature of the metal has decreased slightly and surface films form more readily. They are evidently too weak to stop the flow but too strong to allow the flowing stream to wash them completely away and fill the mold cavity. The surface tension of the metal at this stage may be great enough to account for the rounded and undersize cross-section of the test piece in this region. The peculiarly rippled portion extends for a distance which is clearly dependent upon temperature and is finally replaced by a smooth, clear cut, and well filled portion which extends to the end of the spiral. This seemingly anomalous return to form, after passing through what appeared to be a region of rapid solidification is much harder to explain. About the only theory that satisfactorily explains this is that as the metal cools there is a change in the character of the films, or in the tendency of the films to form, surface tension as influenced by these films is less, and the metal again faithfully fills the mold cavity.

116. The possibility that mold gases might have a bearing was considered until it was found that spirals cast in dry or cement sand gave the same results as those cast in green sand.

117. The influence of turbulent and laminar flow, as they may exist in the respective regions, also was considered carefully but this failed to account satisfactorily for all conditions. If these factors were operative, a series of turbulence cavities would be present, but these are not always in evidence, and when found, they bear no consistent relationship to surface characteristics.

118. At the tip of several of the test pieces, a small, uniform ball of metal was found at the center of the cross-section of the

solidified channel. In a few cases, this round spot was sucked back, forming a small cavity, indicating that at times a negative pressure exists and at other times inertia head pressure is great enough up to the last instant of solidification to force the small column of metal at the center against the end film, rupture it, and form a tiny button. Thus a small volume of metal continues to flow even after heavy walls have solidified around it. This phenomenon also rules out the possibility of basing zero fluidity on the liquidus or solidus of any particular steel, and further supports the marginal zone suggestion.

Influence of Form of Inlet into the Flow Channel

119. To decrease a possible tendency toward turbulence with a less abrupt entrance from the button into the spiral, a gradually tapered inlet was cut in the mold and several tests made. In some tests, the taper was made with an opening 1½-in. wide by 0.4-in. deep, which decreased gradually to the dimension of the spiral over lengths varying in separate molds from ½-in. to 2½-in. Tests were made by pouring molds in pairs, a modified type and a regular type, at several different temperatures. In all cases, the only effect on spiral length was to set the zero point ahead by an amount equal to the length of the tapered section.

Influence of Alloying Elements on Surface Appearance of the Castings

120. A superficial examination was made of the surfaces of all spirals resulting from each test run and conclusions were drawn, in a general way, in regard to the influence of the various elements as they varied in concentration.

121. Concerning the effect of carbon in amounts 0.07, 0.40, and 0.85 per cent, it was observed that the higher the carbon, the more faithful was the mold reproduction. Progressive increases in carbon content seemed to be beneficial and at 0.85 per cent the casting was very sharp and clear cut. Likewise a progressive increase in the tendency for metal penetration into the sand was noted as surfaces were considerably marbled and rough with high carbon. The low carbon steels showed a pronounced rounded section in the central length of the spiral. Although still noticeable at the higher carbon contents, this section was shorter and less prominent.

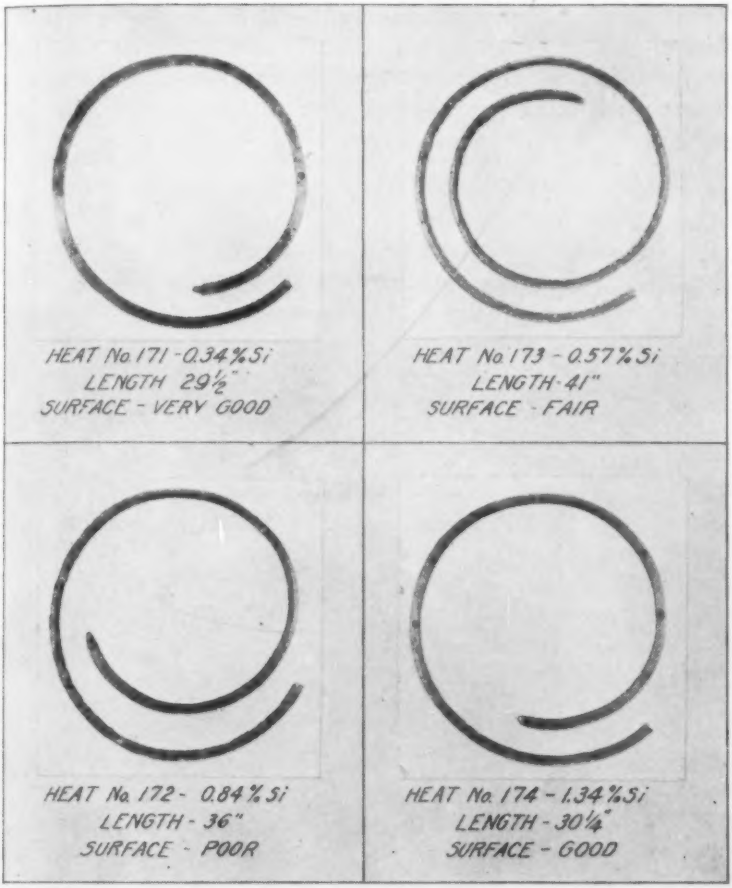


FIG. 57—INFLUENCE OF SILICON ON THE LENGTH AND SURFACE APPEARANCE OF SPIRAL. POURING TEMPERATURE—1540°C. (2804°F.).

122. The effect of silicon in ingot iron on mold reproduction was curious in that decreasingly sharp castings were obtained as the percentage increased from 0.20 to roughly 0.60 per cent silicon. This concentration seemed to give the poorest mold copying quality as further increases to 1.5 per cent gave increasingly better appearance. At 0.57 per cent silicon, the spiral was rounded and slightly undersize for nearly its entire length. Clearly this feature would not be troublesome in heavier sections, except that normally sharp corners might be slightly rounded and imperfectly reproduced. Figure 57 includes this series. In medium carbon steels,

this trend was not as noticeable, but a slight tendency toward the rounded portion in the central section was apparent between 0.50 and 0.80 per cent silicon. Further increases in silicon to 2.5 per cent gave good mold reproduction.

123. Manganese showed the greatest influence on surface appearance of any element studied. At 0.75 per cent manganese in a 0.35 per cent silicon, 0.18 per cent carbon steel, the mold was faithfully reproduced throughout the spiral length. At a concentration of roughly 3 per cent manganese, a great many laps appeared and the surface was rough and irregular, while at 5 per cent, the

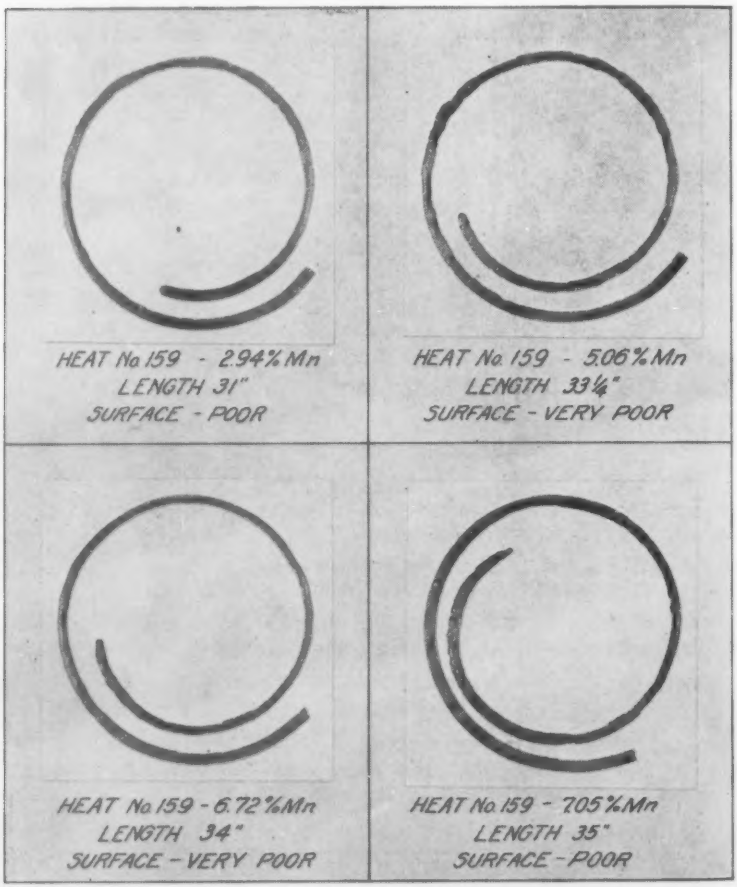


FIG. 58—INFLUENCE OF MANGANESE ON THE LENGTH AND APPEARANCE OF SPIRALS. POURING TEMPERATURE—1625°C. (2957°F.).

surface of the spiral was more lapped and rippled than for any other steel tested. At 7 per cent, the laps decreased markedly but the cross-section was still rounded and undersize. The silicon content changed gradually with successive manganese additions from 0.35 per cent at 0.75 per cent manganese to 1.33 per cent at 7 per cent of the element. Figure 58 shows typical spirals taken from the series of heat number 159.

124. Regarding chromium, as the amount of this element was increased to 2.75, 5.5, and 9 per cent, the casting surface became increasingly better. At 2.8 per cent chromium, the mold reproduction was poor with pronounced lapping, but improved as the concentration was increased to 5.6 per cent until finally at 8.8 per cent the castings were sharp and smooth. The mold reproduction was not quite as good as the plain carbon steel, but nearly so.

125. Nickel, in amounts up to 3.2 per cent, gave poor mold reproduction in the central part of the spiral. With more than this amount, the casting was sharper but still inferior to a plain carbon steel. The beginning and end of the spiral sections were always clear cut and gave distinct mold outlines. Again it might be well to emphasize that this would not prevent getting satisfactory castings unless extremely sharp corners were essential. This effect is possibly a direct result of an increased surface tension or film toughness peculiar to some steels.

126. Copper seems to improve mold reproduction when present in carbon or nickel bearing steels, and it is known that the copper steels previously referred to are satisfactory for casting long thin members.

127. No pronounced or unusual influence was noted for molybdenum and vanadium additions as they were varied over the narrow range of the present tests.

128. The highly fluid nickel-silicon-manganese steel of heat 169 gave a faithful reproduction of the mold except for the central section which was rounded and slightly undersize. The copper-silicon-manganese analysis gave somewhat better results in this respect.

129. As shown in Fig. 36, the use of a mold wash on a dry sand mold yields smoother and sharper castings than were obtained in either plain dry sand or green sand.

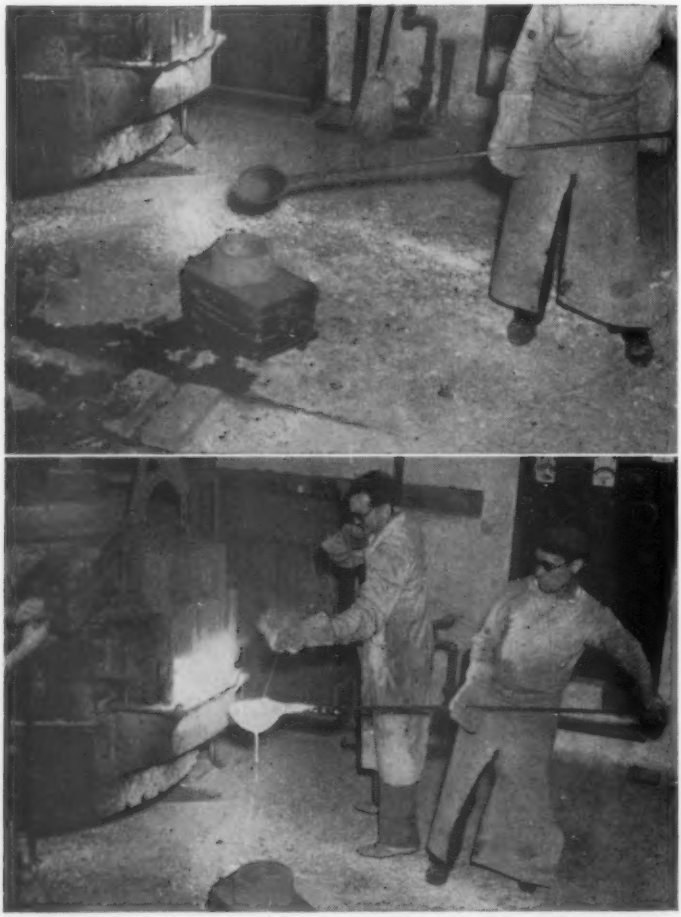


FIG. 59—(TOP)—FLUIDITY TEST MOLD READY FOR USE AT THE ARC FURNACE TO DETERMINE PROPER TAPPING TIME. (BOTTOM)—REMOVING SAMPLE FROM THE FURNACE AND STIRRING IN THE ALUMINUM.

RECOMMENDATIONS

Fluidity Spirals as a Furnace Control Measure

130. In addition to such benefits as can be realized by further shop testing and by the application of the various principles brought out in the discussion of experimental results, there remains the adoption of the laboratory test piece for routine foundry practice.

131. The Naval Research Laboratory spiral mold can be used

for making tests on steel at the furnace before tapping. The technique involved is simple and the time of testing is short. The modified spiral mold possesses the features of convenience, economy, and dependability required of a test piece of this type. Since an actual casting is involved, the length of flow is the result of all factors which influence the fluid life of the steel and it is possible to accurately predict in advance how the molten metal will handle on the floor. By taking samples (the number depending on familiarity with test and furnace operation), it is possible to follow

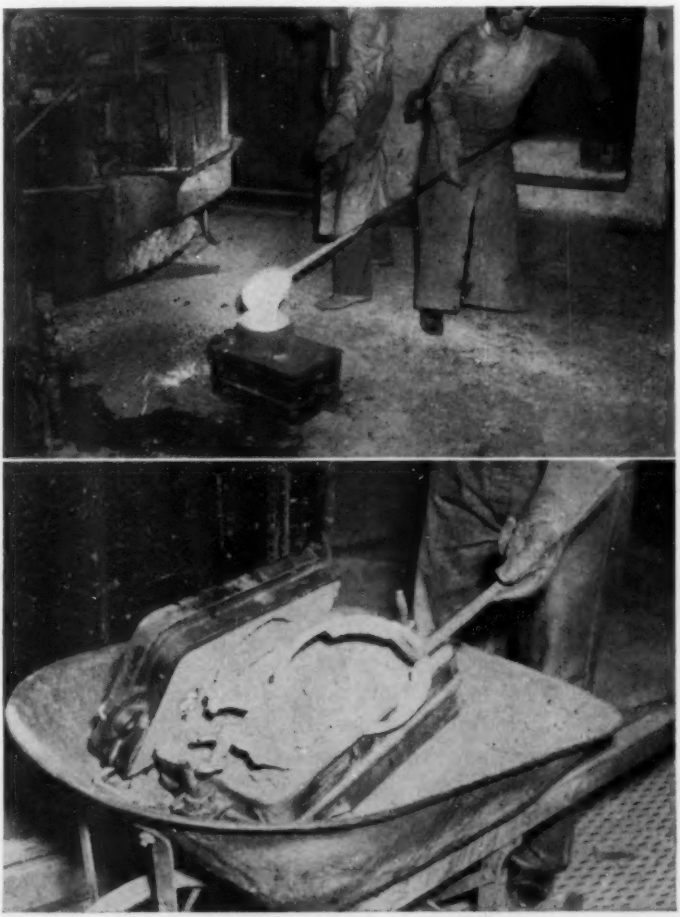


FIG. 60—(TOP)—POURING THE SPIRAL TEST CASTING. (BOTTOM)—COUNTING THE SPIRAL LENGTH AS A MEANS OF DETERMINING THE FLUIDITY.

the progress of the heat from the melt down to the instant of tapping.

132. Not only is it possible to follow the progress of the heat by the use of the spiral test piece, but it is also possible to determine the effects of changes in slag or charging practice, alloying elements, and types, amounts, time, and order of adding deoxidizers. For example, it is possible to show such effects as an increase (often as much as 30-40 per cent but usually much less) resulting from final silicon additions. The magnitude of this increase will be governed by the state of oxidation of the steel before the silicon is added. Further, if such a test becomes standard practice, much valuable information will be obtained on the relative fluidity of steel made in acid and basic open hearth, acid and basic electric, induction, and Bessemer furnaces.

133. The details and photographs of the Naval Research Laboratory spiral test piece for use at the furnace are given in Figs. 5, 6 and 10 to 17 inclusive. The mold may be green sand, dry sand, or cement sand prepared as in normal practice. When ready to use, it is placed in a convenient position near the furnace door, clamped, and a pouring runner set in place over the catch basin. Figures 59 and 60 show the steps in making the test. A sampling spoon (about 10-lb. capacity) is warmed above the bath and well slagged to prevent unnecessary chilling of the metal. When properly slagged, the spoon is plunged deeply into the bath and filled with steel. It is withdrawn from the furnace, 0.4 ounce of aluminum (3/16-in. wide and 1/16-in. thick by 12-in. long, strip wound on the end of a small iron rod) is stirred vigorously into the steel and the contents of the spoon is quickly poured into the pouring runner. The casting solidifies immediately and can be shaken from the mold.

134. The length of spiral is a direct measure of the castability of the steel, and has proved of great value as a control method for operating the arc furnace at the Naval Research Laboratory.

135. It is recommended that serious thought on the part of men in charge of foundry practice be given to the adoption of this test method in the hope of clarifying and preventing many current founding ills. The results of such tests may not appear of immediate value to highly skilled melters or to men in charge

of foundries operating with a minimum of trouble. However, less fortunate operators will welcome any information they can get, and there is little doubt that fundamental benefits will be realized by all who contribute their efforts.

Summary and Conclusions

136. The Naval Research Laboratory modification of the Saeger-Bureau of Standards fluidity spiral has proved suitable for testing the running qualities of molten steel. It is useful and fully satisfactory for evaluating the castability of steel before tapping the furnace. The spiral can be used to full advantage by pouring directly from an induction furnace or on the pouring floor with 1-ton or smaller ladles.

137. The small diameter, straight bar test mold, recommended first by Ruff, is not dependable as a control tool unless provided with a controlled head of metal. Even with this modification, the latitude of flow is too small for maximum dependability. Under carefully controlled conditions, the length of flow averaged 42 per cent that of the Naval Research Laboratory spirals poured from a common feeder.

138. The length of the Ruff mold, the limited length of the casting, and the large dispersion of test results are annoying features in the use of this type. The compactness of the Naval Research Laboratory mold and the excellent reproducibility of results attest to the superiority of the spiral type over the straight bar.

139. A straight flow channel of the same dimensions as the spiral gave 15 per cent greater lengths of flow indicating that some resistance to flow is set up by the constantly changing direction of the spiral.

140. Pouring height, as varied from 2 to 10 in. had no effect on the length of spiral as poured in the Naval Research Laboratory mold.

141. Cement sand and bentonite-bonded green sand and dry sand gave equal lengths of flow, indicating no selective influence of these molding mediums on the fluidity of cast steel as measured by the spiral. Mold washes gave slightly shorter spirals but improved mold reproduction and casting surface. Spirals cast in naturally-bonded green sand gave longer lengths of flow than when

cast in dried sand. Sand grain size was found to have no effect on fluidity over the range of grain fineness from A.F.A. 53 to 123.

142. Carbon has a slight influence on fluidity as it varies from the small amount present in ingot iron to 0.80 per cent. Maximum fluidity was found for ingot iron, dropping somewhat at 0.40 per cent carbon and being restored to an intermediate value at 0.80 per cent. While these results were obtained on steels containing 1.25 per cent silicon, the same general trend was found in unkilled steels as well as in commercial steels. The order of magnitude varied, however, according to the degree of deoxidation and silicon content.

143. Silicon has a marked effect on castability, increasing it progressively to roughly 0.60 per cent silicon and maintaining its beneficial influence for additions as high as 1.25 per cent silicon in plain carbon and alloy steels. In ingot iron, the maximum spiral length is reached at 0.60 per cent silicon, further increases bringing about a lowered fluidity. The difference between medium carbon steels, as silicon varies from 0.25 to 0.45 per cent, is very marked with a great advantage in favor of the higher concentration. This condition is not due presumably to the effect of silicon addition as such but due to the state of deoxidation of the steel.

144. Iron oxide, when added to a steel containing 1.2 per cent aluminum, increased fluidity greatly. This and other results indicate that a certain critical degree of deoxidation is essential to maximum fluidity. Variations either above or below this value operate to decrease fluidity.

145. Silicon, in amounts normally present in commercial steels, has a much greater effect on fluidity than manganese. A manganese-free ingot iron containing at the outset 0.30 per cent silicon gave reasonably good lengths of flow, whereas a silicon-free steel containing a normal percentage of manganese exhibited very poor fluid characteristics.

146. As manganese increases above 1.5-2 per cent in a plain carbon steel, fluidity is greatly improved at lower temperatures, but at higher temperatures, manganese-rich steels are inferior to plain carbon steels in castability. The soundness of the casting may be impaired if high manganese steels are poured at temperatures normally employed for plain carbon or low alloy steels. It

is necessary to use a modified technique in handling Hadfield type steels.

147. For a weight percentage, aluminum was found to be more effective than silicon in promoting fluidity, especially at lower temperatures. This is no doubt due to its greater deoxidizing power. Aluminum is very effective in promoting satisfactory fluidity in steels low in silicon. As aluminum was added beyond 0.2 per cent, fluidity was progressively decreased to an extremely low value at 1.2 per cent aluminum. This indicates that the amount of aluminum for maximum fluid life is critical, but the threshold value is probably dependent upon the previous history and state of oxidation of the bath prior to the addition of the element.

148. Estimates of the fluid character of steels on the basis of visual appearance are likely to be very misleading. Some steels which appear dull and sluggish to the eye frequently have better fluid life than others apparently far more lively. The emissivity of steel varies with different alloying elements and with their concentrations.

149. Copper additions to plain carbon steel increase fluidity progressively as the concentration increases to roughly 4 per cent. At 6 per cent, the length of spiral shows no increase over 4 per cent copper, and 7 per cent copper actually shortens the length of flow.

150. Nickel improves the fluidity of cast steel progressively by successive additions up to 3.25 per cent. Higher concentrations, up to 5 per cent, result in shorter lengths of flow. Characteristic of this class of steel is a sharp initial increase in fluidity at low temperatures and a steady rise up to 1700°C. (3092°F.) beyond the first break at 1500°C. (2732°F).

151. Substantial additions of chromium to steel decrease the fluidity as compared with plain carbon steel. Curves for the 2.8, 5.6, and 8.8 per cent chromium steels were nearly identical throughout the temperature range investigated, with a slight improvement in spiral length at the higher percentages. Except for a small portion at very low temperatures, the curves for chromium steels are a linear function of the temperature to 1700°C.

152. Molybdenum and vanadium when added to a normal plain carbon steel in amounts between 0.25 and 1 per cent caused a reduction in length of flow.

153. A copper-silicon-manganese cast steel containing roughly 1.75, 1.25, and 1 per cent, respectively, of these elements, possesses extremely good fluidity throughout the complete range of normal pouring temperatures.

154. A nickel-silicon steel, developed at the Naval Research Laboratory for maximum castability, possesses the greatest fluid life of any analysis tested. Its composition is roughly 3.25 per cent nickel, 1.25 per cent silicon, 1 per cent manganese, and 0.15-0.20 per cent carbon.

155. The rate of flow of the metal stream through small ingates and thin members can influence the ability of cast steel to fill a mold. Excessive rates of pouring actually decrease spiral length while slower rates of pouring, within critical ranges, yield maximum values.

156. At elevated temperatures, the increment of increase in length of test piece for a given increment of temperature increase is normally smaller than that caused by a similar increment at lower temperatures. This explains the usual breaking over of the curves at a temperature which depends on the type and state of deoxidation of the steel. Basing the point of zero fluidity on either the solidus or liquidus of a particular material, is not good practice. Also predictions of fluidity from an equilibrium diagram will normally yield erroneous and misleading conclusions when applied to foundry practice. Conditions of oxidation and the amount and nature of any alloys present serve to mask the effect of shifts in liquidus and solidus temperatures. In some steel analyses, however, fluidity appears to be related to the equilibrium diagram.

157. The reproducibility of results in the work included in this report, as well as results from use of the spiral mold at the arc furnace, attest to the practicability and simplicity of the mold as a test piece for evaluating the running qualities (fluidity) of cast steel.

ACKNOWLEDGMENTS

158. It is with much pleasure that grateful acknowledgment can be made herein to the following men who aided in this work and without whose cooperation this paper would not have been possible: R. A. Gezelius, who was intimately concerned with and

active in the development and initial testing of the spiral fluidity mold when he was associated with this laboratory; James Darby, Roy Donaldson, and Robert Morey for their assistance and contributions throughout the test work; Thomas Cunningham for his indispensable foundry abilities; Louis Singer for chemical analyses; and I. R. Kramer and Harold Bishop for their assistance. The authors also wish to express their appreciation to those men in industry and research who were kind enough to review the work, and, in particular, to Dr. R. H. Canfield and Dr. F. M. Walters, of the Division of Physical Metallurgy at this laboratory, for editing the manuscript and for encouraging the work. The authors are also greatly indebted to the Navy Department for sponsoring the work and for permission to publish the results.

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DISCUSSION

Presiding: F. A. MELMOTH, Detroit Steel Casting Co., Detroit, Mich.

W. J. PHILLIPS[1]: In the manufacture of very low carbon steels, we have observed that with our carbon under 0.10 per cent and manganese under 0.10 per cent the fluidity is greater, than it is with the carbon around 0.15 per cent and the same manganese and silicon content. Also, with that fluidity increase, there is a resistance to hot tearing, with very low manganese around 0.04 per cent. Hot tearing is much more pronounced when the carbon approaches 0.15 per cent. There is quite a critical point. We have tried to explain this phenomena by the postulation that Messrs. Briggs and Gezelius made, namely, that some of the hot tearing might be later filled in with fluid steel. We have observed that.

H. D. PHILLIPS[2]: This paper confirms the opinions of practical foundrymen gained through years of experience in dealing with fluidity of cast steel. The observations of George Batty and Chairman Fred Melmoth on over-reduced steels, the lack of fluidity of certain steels when they were low in iron oxide content, and so on, is confirmed.

C. E. SIMS[3]: I had an opportunity to read this paper in the preliminary form and was greatly impressed by the amount of work that has been done. The method developed for testing is comparatively new and the authors have shown considerable ingenuity in adopting the spiral test and eliminating most of the variables that are due to the human element. The data are here, but the interpretation of these results necessarily will have to continue for several years. They are all too n[illegible]

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[2]Plant Manager, Lebanon Steel Foundry, Lebanon, Pa.
[3]Supervising Metallurgist, Battelle Memorial Institute, Columbus, O.

yet to be able to evaluate them properly. And in the interpretation of these data certain difficulties arise. Some of the results should have been plotted as three dimensional curves to show the full effect, because whenever you add one thing to a steel you may cause some other change to take place. For example, if a steel contains a deoxidizer, silicon, manganese or aluminum, and iron oxide is added you are doing two things, building up iron oxide and at the same time removing silica or aluminum. So a combined effect is obtained. The full significance of some of these effects tends to be a little obscure. In this connection, adding two elements sometimes gives unexpected effects. The effect of adding one element at a time to steel is sometimes very different from adding two at the same time.

The most striking example I know of was obtained in some fluidity tests made at Battelle. In this work increases of silicon above the normal content were found to increase the flowability, and titanium additions were found to have very little effect. But when both high silicon and titanium were used together the fluidity suffered greatly. There may be other combined effects similar to this.

With such materials as aluminum there are tough films formed that sometimes interfere with the flow of the steel. As Mr. Taylor pointed out this property he calls fluidity is really the integration of a number of factors. We found that when small quantities of aluminum were added to cast steels that there was first a decrease in fluidity and then with slightly greater additions an increase. No tests were made using the large additions reported here.

The so-called silico-manganese steels containing about 2.00 per cent of silicon seem to be excessively fluid. I do not have any fluidity test data but when cast, these steels have a strong tendency to form paper thin fins that run out to great distances at the mold parting. It seems almost impossible to make a mold tight enough to prevent leakage. This steel will run through wire vents a distance of 6 to 8-in. Mr. Taylor has intimated that he thinks this a different type of fluidity than is measured by the fluidity test. I would like to have him comment on this.

At the other extreme the high chromium steels often appear cold and sluggish and yet flow surprisingly well. It is an oxide film that gives the sluggish appearance, but when properly handled this film does not greatly interfere with the filling of the mold.

MR. TAYLOR: Concerning titanium and its influence on high silicon steels, our experience corroborated Battelle's. When we added titanium to high silicon steel we drastically reduced fluidity. This phase of the work was not carried to completion. Several such things were not, but we hope to be able to investigate various deoxidizers more fully at a later date. Titanium is conspicuous in this work by its absence which was definitely not intentional. We had to stop somewhere so we stopped short of that. There were other things we hoped to include, too, and titanium is one of the first elements we will investigate in further work.

Regarding three dimensional diagrams as mentioned by Mr. Sims; these would be a paper in themselves. To cover even one set of deoxi-

dizers completely would be a major problem over a rather long period of time. We were trying to generalize our work, to put it in practical terms, and although three dimensional diagrams would undoubtedly be practical, we felt we should present the information we have in the simplest way possible before taking more time to figure out the various angles.

I purposely avoided a discussion of surface films because of the limited time. It would take quite a while to go through the effects of these various elements. It is all in the text, and as Mr. Sims points out, these films are important. They will affect the fluidity, and by that we mean foundrymen's fluidity and not fluidity as the reciprocal of viscosity. We have tried to give the word "fluidity" a little push. Perhaps "flowability" would be somewhat better, though it is not used in the industry. It would be advantageous for a nomenclature committee to decide on the best word.

Regarding the high fluidity of 2.00 per cent silicon steels, we realize that discrepancies may exist and that the complete picture on silicon is not presented. We have more to do on this element. Mention was made in correspondence with Mr. Sims, that the tendency of these steels to form fins or to flow into little vent holes did not seem to tie up with the fluidity as measured by the spiral. A good deal more work has to be done to find out what relationship does exist. We expect to find that instead of the fluidity dropping back at 0.80 per cent silicon in all cases, it will vary somewhat depending upon the previous history of the steel. We checked this very carefully but will have to consider it in detail later.

A steel containing chromium appears considerably hotter than it really is. I have not noticed that it affects the optical pyrometer but it certainly affects the eye that way. If you stand in front of a crucible of chromium steel you get hot much faster than you will with any other steel.

WERNER FINSTER[4] (*Written discussion*): This paper contains such a vast amount of information that it will be impossible to discuss it in detail. Fluidity always has been a "bone of contention" between melting and molding departments. Mr. Taylor and his co-workers have developed a method by which fluidity can be evaluated and any tool which will enable us to record fluidity in terms of definite values should be welcomed by the foundry industry.

Mr. Taylor was kind enough to send us one set of patterns for the fluidity test mold and L. E. Obrzut, of our organization, did some preliminary work on fluidity. My contribution to the discussion on Mr. Taylor's paper, therefore, will be limited to reporting some of the observations which were made on the application of the fluidity spiral to foundry practice. First let me state that the fluidity mold was only applied to record existing conditions in melting practice and the mold so far has not been applied as a control medium, as the number of tests made has been too small. In conjunction with the fluidity tests also

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slag tests were made using the Herty viscosimeter. All heats were made in a three-ton electric furnace with acid lining. On all fluidity tests the molds were made in green sand and 0.4 oz. of aluminum was stirred into the test spoon. Two sets of fluidity tests were taken on each heat on which the tests were made, the first test was taken prior to the final addition of ferro-silicon and ferro-manganese and the second test after these additions had been made.

1. The first group of tests consisted of 13 carbon steel heats made to Navy Class B Specification. The chemical analyses of these heats were within a fairly narrow range with carbon between 0.20 - 0.24 per cent; manganese 0.60 - 0.73 per cent and silicon 0.24 - 0.31 per cent, with the exception of one heat on which manganese was 0.81 per cent and silicon 0.35 per cent. Temperature readings were taken at "tap" with an optical pyrometer and a close relationship was found between tapping temperatures and fluidity, that is, fluidity increased with increase in tapping temperature. In an attempt to correlate fluidity with k.w. hr. input per ton, a less clearly defined relationship was found, though the heat which had the highest fluidity also had the highest k.w. hr. input per ton. K.w. hr. input per ton on these heats varied between 470 and 530 with an average of 485. On the first samples taken prior to the addition of ferro-silicon and ferro-manganese, fluidity, as expressed in inches, ran from 19 to 25-in. The second samples, taken prior to tapping, showed fluidity readings of from 21 to 26-in. The increase in fluidity between the first and second test was between 2 and 3-in. The highest result obtained, namely, 26-in. was on the heat which had the highest manganese and silicon content, as well as the highest k.w. hr. input per ton. Observations on the carbon steel fluidity tests indicate lower viscosimeter readings, expressed in inches as measured by the Herty viscosimeter, as final fluidity increases. No relationship could be found between fluidity prior to tapping and the physical properties of the heats as may be expected, as the control test blocks were poured only during the middle of the pouring operation. On many of these heats, metal was shanked, fluidity spirals were poured on these shank heats from the tenth to fifteenth shank poured from a heat. Fluidity readings obtained in these tests varied over a much wider range than readings taken before tapping. This was due to variables in the shanking operation and while the average reading obtained from the tenth to fifteenth shank was 15½-in. and at the end of the shanking operation was 10-in. the results did not lend themselves to establish correlation with the fluidity results obtained at the furnace prior to tapping.

2. The second group of steels on which fluidity tests were taken were nickel-chrome-molybdenum steel heats, Type C-11 of A.S.T.M. Specification A-157. The chemical analyses on the seven heats in this group again were within a fairly narrow range with carbon 0.29 - 0.33 per cent; silicon 0.29 - 0.33 per cent; manganese 0.65 - 0.78 per cent; chromium 0.70 - 0.80 per cent; nickel 1.44 - 1.85 per cent and molybdenum 0.26 - 0.36 per cent. Samples taken prior to the final additions ran from 22½ to 31-in. whereas samples taken after the final additions

ran from 25 to 33-in. Again we find an average increase of 2 to 3-in. between the first and second tests. On this group of steels a closer relation between k.w. hr. input and final fluidity was noted showing an increase in fluidity with increase on k.w. hr. per ton. The k.w. hr. input on these heats varied between 475 and 550 per ton with an average over 510. Slag viscosimeter readings gave no clearly defined relationship. However, the heats higher in nickel showed increased fluidity which, while in line with the author's observations, may in this case only be coincidental. Observations on the castings poured from this group of heats which had a final fluidity of 25 to 33-in. showed that the castings had good surface appearances with only slight fusion on a few.

3. The third group of steels, eleven heats of 4.00 - 6.00 per cent chrome-molybdenum steel, Type C-5A of A.S.T.M. A-157 were investigated. Variations in chemical analyses in this group of steels fell between the following values: carbon 0.18 - 0.21 per cent; manganese 0.56 - 0.76 per cent; silicon 0.26 - 0.44 per cent; chromium 4.80 - 5.80 per cent; molybdenum 0.40 - 0.54 per cent. Results on the fluidity spirals poured prior to the addition of ferro-silicon and ferro-manganese showed fluidity measuring 15 to 32-in. and on the spirals after the additions 20 to 37½-in. K.w. hr. input varied between 500 - 625 per ton and the results showed an indication that again fluidity increased with increase in power input. Slag viscosimeter readings decreased as the final fluidity increased. The heats which were on the high side of the silicon range indicated above, namely, 0.36 to 0.44 per cent silicon, also had, with one exception, higher fluidity. As this type of steel has a tendency to create wrinkles and laps on the surface of the castings, the purpose of employing the fluidity test mold on this group of steels was to find a correlationship between fluidity and the appearance of wrinkles on the casting surfaces. As pouring conditions, gating and mass involved all enter into this picture, the correlation was not clearly defined except that it can be stated that the castings poured from the heat which gave a 20-in. spiral length were very badly wrinkled, whereas the castings poured from the heat which showed 37½-in. spiral length were free from all wrinkles, but showed some slight fusion. Indication exists that with the melting and foundry practices employed at our plant, fluidity spiral readings above 30-in. should be obtained prior to tapping to secure the desired casting surface appearance.

The authors have called attention to the appearance of the metal in the test spirals which at the beginning of the spiral shows a smooth surface filling the cross-section of the spiral cavity, then a section which has a wrinkled appearance with the end section of the spiral again being smooth.

On the series of nickel-chrome-molybdenum steel heats it was observed that five of the tests taken prior to the addition of the final deoxidizers gave spirals which were free of ripples and very smooth except for some fusion near the down gate; whereas the spirals on these heats taken after the addition of silicon and manganese showed

a rippled section which, however, was not always at the same part of the spiral. On the 4.00 - 6.00 per cent chrome heats the first tests showed a slight ripple, whereas the second set of fluidity spirals on those heats showed a badly rippled section which again started and ended not always at the same length of spiral. As the authors have tried to explain this behavior with the flow of metal in the spiral, I would appreciate their comments on why the nickel-chrome-molybdenum steel spirals, taken prior to the addition of ferro-silicon and ferro-manganese smooth surfaces were obtained, whereas the spirals showed a rippled section after the final additions. Both sets of spirals had been poured with steel killed by 0.4 oz. of aluminum.

In citing our experience with the fluidity mold, I wish to emphasize that the number of tests made is too limited to draw conclusions and that a great deal of work will have to be done before a more clearly defined picture can be gained.

MR. TAYLOR: We appreciate such contributions whether they are in confirmation or condemnation of our work. Our chief hope for fluidity testing is that if it is useful it will enjoy a wide practical application and if it is not useful, it will be proved so. So far, from the tests we have made, we feel that it has a very useful commercial application.

Regarding those points that Mr. Finster brought out, I have very little to add. We have not worked a great deal with chrome-nickel-molybdenum steels. We do not make a lot of castings, at least not enough to obtain a statistical correlation between results on the floor and fluidity tests. It is with the deepest gratitude that we acknowledge his work as a continuation of ours. It is this sort of thing that we hope will be done. We realize that it is a poor time to do it, because of the urgency of defense work, but if and when it can be done, we will certainly appreciate more of it.

E. C. TROY[5]: This test has been used in the research laboratory primarily to investigate the effect of various factors on fluidity. It could be used as a control tool. Mr. Finster mentioned the tests he has run. Perhaps we can take this instrument into the foundry and use it to obtain better control over the runability of our castings.

It does not seem to me that the word fluidity fits the properties measured. The results of these tests indicate that the fluidity is not a definite measure of the degree to which the steel will take mold contour. Always in the foundry we have felt that steel fluidity or runability would give better mold contour. Mr. Taylor almost told us his theory as to why he feels that this ability to fill a mold is not necessarily a function of fluidity, and I wonder if he would care to discuss this further.

MR. TAYLOR: I believe what I said was that the faithfulness of the

[5]Metallurgist, Dodge Steel Co., Philadelphia, Pa.

reproduction of the mold was not necessarily a function of inherent fluidity. You can pour steel from the same ladle into two molds and in one it will run the mold sharply and in the other it will not. In comparing dry sand molds and washed and dried sand molds, there is a big difference. The washed mold will give you a much more faithful reproduction and the casting will be clear and sharp. In the mold which is similarly made and treated but without the mold wash, you will get roughnesses of surface and lapping in certain cases.

I also mentioned that the higher carbon steel gave a much more faithful reproduction of mold cavity than the lower or medium carbon steels. So far as my original statement that you could find differences of surface if you pour the same steel in two molds, you could go a little farther. If you compare dried sand molds with green sand molds of the type we use, which may be essentially dry on the surface, then you will not see much difference. But if you compare it with a natural bonded green sand mold of high moisture content you might get some back pressure, an envelope of gas created along the passage, which discourages a faithful reproduction of the mold cavity. The same thing may happen in square corners or internal angles. If gas is created and kicks back, the metal will not lie to the mold surface. A lot of these steels are bad that way but there is too little time for discussing it in great detail. I just want to mention that we use the spiral religiously as a control of our furnace at the laboratory. We set upon an arbitrary length of flow and by meeting that figure we have no trouble whatever from lack of fluidity.

JOHN HOWE HALL[6]: Fig. 48 illustrates exceedingly well a fact that is well known to the makers of manganese steel, which is that they can get very high fluidity with that metal at temperatures at which one could not think of pouring carbon steel. In the paper emphasis is laid on the desirability of pouring manganese steel at as low a temperature as is possible. There are reasons, aside from the mere flowability, why it is desirable to pour manganese steel at low temperatures. The lower the temperature at which it is poured, the finer the microstructure and the stronger the casting.

My comment to Mr. Taylor was if we had from 3 to 5 tons of manganese steel to shank off in small castings, we could not begin way down near the solidification point to pour that metal, because if we did we would not pour at all. If you had only 50 lb. of steel to dispose of and, you were pouring chain links, you could start pouring when the steel had cooled almost to the solidification point.

It is quite noticeable that whereas changes in the nature of the steel frequently show marked changes in the fluidity curve, the changes in the material of the mold apparently have no particular effect on this test. On page 39, Fig. 35, in the test showing how long a spiral you can get on green sand, dry sand and dry sand washed, it is noticeable

[6]Consultant, Philadelphia, Pa.

that all those three mold materials are on an even footing. It does not make any difference which one you use. Then you turn over to page 43, Fig. 37, and you have the influence of using either a cement sand or a green sand mold on the fluidity, and again they are the same; steel will flow just as far in green sand as it does in cement. One of the good pieces of work that Messrs. Briggs and Gezelius did a few years ago that did not attract as much attention as it should have, was a paper in which they gave a lot of data on cement sand molding in which they showed that the cement bonded sand takes heat out of the steel much more slowly than either green sand or dry sand that is, a cement sand mold is a wonderful heat blanket. That being so, it seems curious that material that extracts heat from the steel so slowly, should not allow the steel to run any further than it does in the material that subtracts the heat much more rapidly. It makes me wonder whether, so far as the effects of the mold material goes, possibly a test of this size and shape is not as applicable as it is in determining the effect differences in steel composition.

R. A. GEZELIUS[7]: Mr. Hall brought up the point that the cement bonded sands extract heat much slower than other sands. If you visualize a cross-section of the test piece used by the authors, you will realize that the cross-section is so small that the molding medium will have very little effect upon the solidification rate. That is, the initial skin formed due to the cold mold will probably account for practically all of the solidification that occurs. Therefore, the rate of heat transfer through the sand itself will have very little bearing upon the test. I do not believe that, with this test, one can expect to record any large differences in fluidity, due to variations in the molding media.

CHAIRMAN MELMOTH: Mr. Phillips mentioned the effect of adding deoxidizers simultaneously rather than in succession. This is important when we are concerned with silico-manganese. Some years ago, Batty stated that silico-manganese as a deoxidizer of light steel castings reduced fluidity more than equal additions of separate ferro-silicon and ferro-manganese. I believe, also, that Andrew McCance, of England, has done a considerable amount of work along these lines which may be of interest to the author, as indicating that considerable interest was exhibited along these directions quite a number of years ago.

There was one other point in the paper that I noted myself that affects my consideration of it. I am not sure that you can take a curve of the type submitted and say that the fluidity shown with an increasing quantity of carbon is an indication definitely of the influence of that carbon on steel. The low carbon steels are declared to have higher fluidity than the higher carbon materials. I wonder whether this can be taken as the literal effect of carbon on iron, or whether it is due to some extent, at least, to the process used in the making of these particular steels. For instance, in the low carbon steels one has a highly

[7]Metallurgist, General Steel Casting Corp., Eddystone, Pa.

oxidized bath, and the oxidizing condition is carried a long way down in the process. It therefore produces the ideal condition to give the maximum fluidity irrespective of carbon content. Then in the intermediate range one has an intermediate set of conditions, whereas in the high carbon range one tends to wipe out the conditions which have been introduced by the melting procedure. Is it not possible that the apparent fluidity changes are a reflection of the method of procedure as well as being a reflection of the direct influence of carbon content?

This is not meant to be a criticism, but I think sometimes we have to consider such things from more than one point of view. It may be that when this work has been developed even more (and it is only at its beginning, although it looks so big) many of these questions will be answered.

MR. TAYLOR: We are very pleased to know that the reaction of the chairman is to "make haste slowly." The last thing in the world we would care for is an immediate acceptance of the information presented in this paper before time has proved or disproved its merit. It is hoped that such an attitude will be prevalent and that it will lead to further individual work along these lines for only from such an effort can the whole truth be gleaned. We tried to bring out in the text the paramount influence upon fluidity of the state of oxidation of the steel and certainly this quantity is greatly influenced by the alloy content and previous history of the steel. The hidebound acceptance of these curves as a guide in commercial steel making practice was not the aim of the publication nor the desire of the authors. The treatment was entirely too general for such a utopian accomplishment. The statement "it is clear that little practical advantage can be taken of the effect of carbon on fluidity, except perhaps at lower temperatures on well killed steels," seems to present a fair case for carbon from the data at hand. Real value will come from this work only when steel makers are able to weigh the tools and technique of fluidity testing developed in the light of their own practical experience.

MR. BRIGGS: It must be remembered that in a discussion of fluidity of steel, the mold into which the steel is poured must be considered as an essential part of the test. Thus, the term fluidity applies equally well to mold conditions as it does to metal characteristics and conditions of the test. The fact that under certain conditions the steel reproduces the mold cavity better than it does at other times is a manifestation of the great number of things that the term fluidity includes. It is definitely our belief that surface oxide films, surface tension and gas pressure are very important considerations in the study of fluidity.

It is quite possible that a spiral cross section with its minimum amount of mold metal contact is not the best test piece to study the effect of surface oxide films, surface tension and gas pressure. In fact, we are inclined to believe that it definitely is not the proper shape to study these variables. In this work we have endeavored to keep variables

and the effect of variables to a minimum in an attempt to present information mostly on the steel characteristics. Please do not misunderstand that in our attempt to devote most of our attention to steel characteristics we have forgotten that the term fluidity is all embracing, for such is our understanding of the term.

The complete picture of all the conditions of fluidity may probably never be made, it being extremely difficult to evaluate the effect of certain of the variables involved.

Deoxidation followed by surface oxidation of the metal in the mold is going to vary depending on the combination of deoxidizers used. Thus, two additions together may change the fluidity results materially from what was found by single separate additions. The percentage of each element used in the double addition may be important. Also, the mold conditions may affect the fluidity resulting from the separate single additions more than the double additions. All of these are important in the consideration of the subject of fluidity.

It has been our attempt to focus thought and throw light on fluidity from the standpoint of the steel characteristics. Reference is made of course to such variations as composition and effect of temperature. Even in this regard we have not presented a complete picture since we know that steel making conditions, total oxygen content of the metal and so forth, are important in the consideration of fluidity. In this regard we have attempted to outline the framework and show effects in a preliminary way under conditions as nearly standard as possible. More complete information may be difficult to present as interpretations of results may not be at all easy or feasible.

Melting in the Cupola

TRANSLATED FROM THE GERMAN, SUMMARIZED AND DISCUSSED

BY S. C. MASSARI* AND R. W. LINDSAY**, CHICAGO, ILL.

Abstract

This paper is a summary of a series of articles, on the process of melting in the cupola, that have been published in various German technical papers over a span of the past 7 years. The material originally was submitted to the American Foundrymen's Association in connection with the work of the Cupola Research Sub-Committee on Fuels and Combustion. However, when the translation was completed, the translators felt that the information contained might be of interest to all members since it is fundamental to cupola operation. A large part of the original articles represent investigations carried out by H. Jungbluth[1] and co-workers, particularly by H. Jungbluth and P. A. Heller[2], and by H. Jungbluth and H. Korschan[3], but frequent references are made to the results of other European and American investigators. A mathematical relation between melting rate and blast volume, coke charge, and the stage of combustion was established as a result of these investigations, as well as a general hypothesis of the mechanism of melting in the cupola. It is felt that the summary will be more interesting and valuable if the general conception of melting is discussed first, leaving the mathematical treatment included as an appendix. In this manner the continuity of thought is not interrupted by mathematical digression, and yet the latter material is available for those who may be interested.

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* Metallurgist and Research Assistant, Association of Manufacturers of Chilled Car Wheels.

[1] Superior numbers refer to bibliography at end of paper.

NOTE: This paper was presented before a Gray Iron session at the 45th Annual A.F.A. Convention, New York City, N. Y., May 13, 1941.

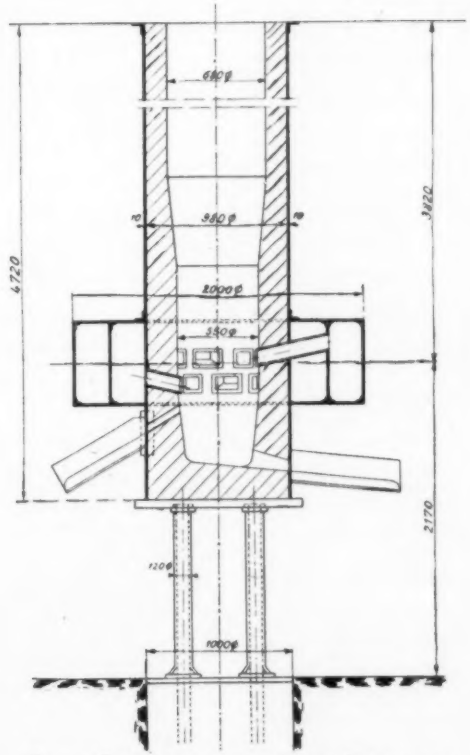

FIG. 1—THE EXPERIMENTAL CUPOLA INSTALLATION.

EXPERIMENTAL PROCEDURE

1. Jungbluth and Korschan conducted their investigations in a small experimental cupola shown cross-sectionally in Fig. 1. The dimensions indicated are in millimeters and consequently to convert to feet, they must be divided by 304.8. This cupola was lined to a diameter of approximately 21½ in. and the height from tuyeres to charging platform was about 12½ ft. Central charging was employed. The blower, driven by a direct current motor, could be controlled between the limits of 353 to 1235 cu. ft. of air per min. (10 to 35 cu. mtrs. per min.). All possible sources of air leakage were eliminated by welding of the blast main and the cupola itself. Blast volumes were accurately measured and also were calculated from formulae. Samples of the stack gas were taken through a water cooled tube located about 1.7 ft. (½ mtr.) below the charging door, analyzed and recorded (with a Mono-

duplex-K apparatus). Control samples, taken by hand, were checked analytically in an Orsat apparatus.

2. The charge consisted of pig iron to avoid carbon absorption and consequent difficulties in the calculations. The pig iron had the following composition:

Total carbon, per cent	4.16
Silicon, per cent	2.21
Manganese, per cent	0.69

A charge, which weighed 660 lb. (300 kg.), was composed of pigs approximately 9 x 4.7 x 4.7 in. (230 x 120 x 120 mm.).

3. The coke used had the following average composition:

Fixed carbon, per cent	88.65
Sulphur, per cent	1.07
Moisture, per cent	2.20
Ash, per cent	6.39

The coke was charged as lumps of about 4 to 5 in. (100 to 130 mm.) diameter and 7 to 8 in. (180 to 200 mm.) length. The bed coke amounted to 440 lb. (200 kg.).

4. The limestone had an average composition of 98.7 per cent $CaCO_3$. It was used in the amount of 6.6 lb. per 220 lb. of iron on 6 to 14 per cent coke charges and 11 lb. per 220 lb. of iron on 16 per cent coke charges. Iron, coke, and limestone were delivered in the same charging bucket, but in separate layers. Each experiment extended over a period of 6 to 8 hours.

THE MECHANISM OF COMBUSTION IN THE CUPOLA

5. A study of the relationship between coke charge and blast volume and their influence on the melting rate and iron temperature permits a close insight into the cupola process of melting. The interdependence of these factors is depicted in Fig. 2.

6. Two facts are immediately apparent from this diagram, namely:

1. If the blast volume is increased while the coke charge is held constant, the melting rate and the temperature of the iron will increase.

2. If the coke charge is increased with constant blast

volume, the melting rate will decrease and the temperature of the iron will increase.

7. The fact that hotter iron is produced under the second set of conditions is taken to be a rather definite indication that the carbon monoxide found in cupola stack gases is formed by reduction of ascending carbon dioxide in the shaft ($CO_2 + C = 2CO$). It is shown in Fig. 3 that the percentage of carbon monoxide increases as the coke charge increases. The increase in percentage of carbon monoxide is represented in this diagram by a decrease in "n_v", where

$$n_v = \frac{\%\ CO_2}{\%\ CO_2 + \%\ CO} \times 100.$$

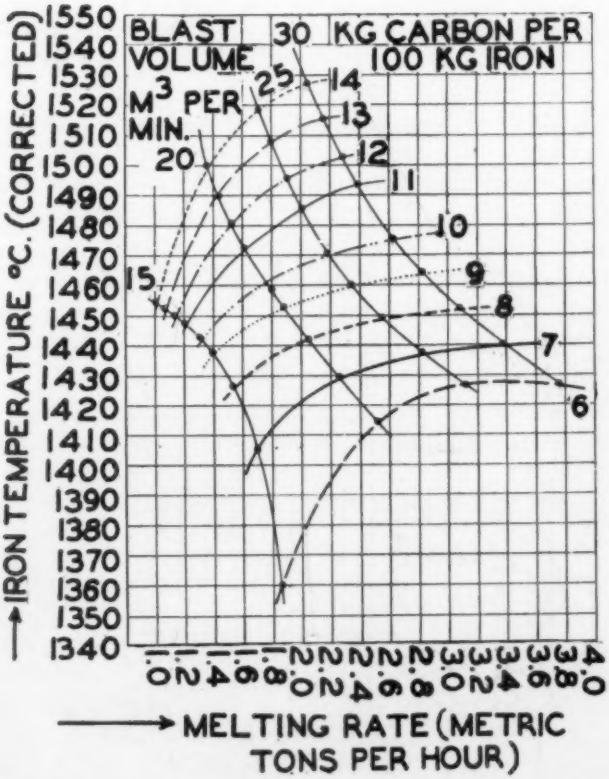

FIG. 2—RELATION BETWEEN MELTING RATE, KG. OF CARBON PER 100 KG. IRON, BLAST AND IRON TEMPERATURE.

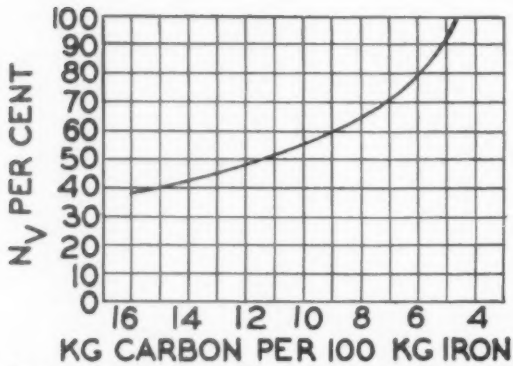

FIG. 3—RELATION BETWEEN N_V AND KG. OF CARBON PER 100 KG. IRON (AFTER H. JUNGBLUTH AND P. A. HELLER).

8. If the theoretical temperatures of combustion corresponding to various ratios of CO_2/CO are calculated and plotted (Fig. 4) it is seen that low theoretical temperatures of combustion are associated with high percentages of carbon monoxide (or low values of "n_v"). The shaded portion of this line is pertinent to cupola operation. If the carbon monoxide is formed by combustion in front of the tuyeres, it creates the impossible situation in which the iron increases in temperature while the zone wherein it acquires its temperature becomes colder. An investigation by Vogel[4] is offered as additional support for the assumption that carbon monoxide forms secondarily as a result of reduction of carbon dioxide. This investigation was conducted in a shaft furnace of 4-in. diameter (100 mm.) filled entirely with coke. The results obtained using foundry coke are evident in Fig. 5.

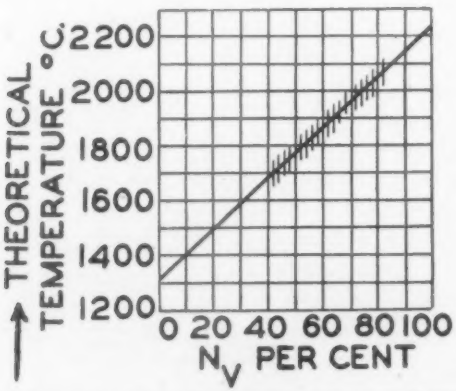

FIG. 4—THEORETICAL COMBUSTION TEMPERATURE WITH VARYING RATIOS OF COMBUSTION N_V.

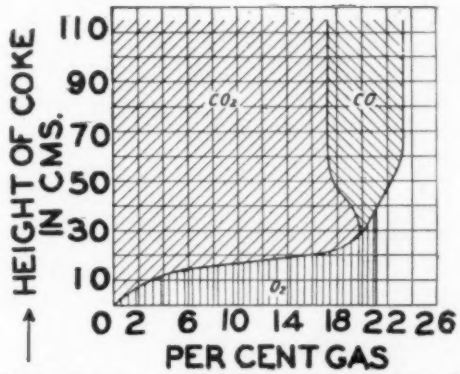

FIG. 5—COMBUSTION IN AN EXPERIMENTAL CUPOLA. (AFTER R. VOGEL.)

9. It may be noted that in Vogel's experiments the original product of combustion was carbon dioxide mixed with unconsumed oxygen. As this mixture ascended through the hot coke, the oxygen present reacted with carbon to form an increasing amount of carbon dioxide, the oxygen completely disappearing at a height of slightly less than 15-in. (38 cm.) above the tuyeres. Meanwhile, carbon monoxide makes its first appearance at a height of almost 12-in. (30 cm.) and increases in amount at the expense of carbon dioxide. The percentage of carbon monoxide increased up until a height of about 23½ in. (60 cm.) was reached, above which level no further reaction occurred and the ratio of CO_2/CO remained constant.

10. Further corroboratory evidence for the hypothesis that carbon monoxide results from reduction of carbon dioxide is offered in investigations by Oberhoffer and Piwowarsky[5], and by A. W. Belden[6]. The former pair of investigators, in connection with an investigation involving the effect of injecting water into the cupola, presented diagrams portraying the gas composition in the various zones of a small cupola of 8.7-in. (220 mm.) diameter, which was filled entirely with coke.

11. Considering that the most extreme condition occurs, namely, that all of the carbon before the tuyeres originally burns to carbon dioxide, rather simple relations are found to exist between the coke charge and melting rate. Furthermore, a simple conception of the mechanism of melting in the cupola can be developed.

12. Obviously equal volumes of blast will always burn the same portion of coke to carbon dioxide in front of the tuyeres over

a period of one hour, regardless of the coke charge. This fact can be portrayed by the formula

$$C_w = \frac{60}{8.9} \times W, \text{ where}$$

C_w = the weight of carbon in kilograms burned by the blast per hour, and

W = the volume of blast per minute in cubic meters. The quantity of air required to burn one kilogram of carbon completely to carbon dioxide is 8.9 cubic meters.

13. The total carbon burned per hour (C_h) can be expressed mathematically as:

$$C_h = \frac{K \times k}{10} \times S, \text{ in which}$$

K = the weight of coke in kilograms used per 100 kilograms of iron,

k = the weight of carbon in 100 kilograms of coke (per cent carbon in coke x 100), and

S = the melting rate in metric tons per hour (1 metric ton = 1000 kg. or 2200 lb.). The formula is arrived at in the following manner:

$$K \times \frac{k}{100} = \text{weight of carbon (in kg.) burned per 100 kg. of iron, and}$$

$$K \times \frac{k}{100} \times 10 = \frac{K \times k}{10} = \text{the weight of carbon used per 1000 kg. of iron melted (10 times that burned per 100 kg. of iron).}$$

This value multiplied by S will then give the weight of carbon burned per hour.

14. The weight of carbon used for reduction of carbon dioxide to carbon monoxide is then equal to

$$C_h - C_w = C_r, \text{ where}$$

C_r = weight of carbon in the coke charge used for reduction of carbon dioxide to carbon monoxide.

15. The amounts of carbon burned by the blast per hour (C_w) and the total carbon consumed per hour (C_h) are recorded in Fig. 6 for various weights of coke (or carbon) used per 100 kg. of iron, the blast being held constant at 1412 cu. ft. (40 cu. mtrs.) per min. It will be seen that under these conditions C_w remains constant and is equal to

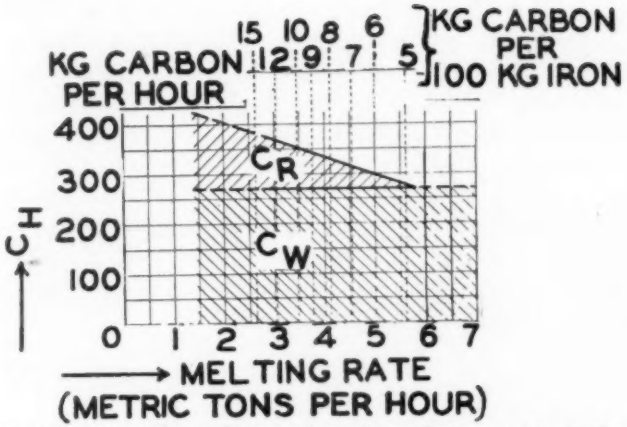

FIG. 6—RELATION BETWEEN MELTING RATE, CARBON BURNED TO CO_2 AND COKE CHARGE WITH CONSTANT BLAST VOLUME.

$$C_w = \frac{60 \times 40}{8.9} = 270 \text{ kg. of carbon per hour.}$$

16. The total carbon burned per hour *(C_h)* of course, is related to the coke-charge and the melting rate. For a coke charge equivalent to 12 kg. of carbon per 100 kg. of iron ($S = 3.05$ tons per hr.) C_h would equal

$$C_h = 12 \times 10 \times 3.05 = 366 \text{ kg. of carbon per hour.}$$

17. Under these conditions

$C_r = 366 - 270 = 96$ kg. of carbon are used per hr. in the reduction of CO_2 to CO.

18. As the coke charge is decreased (Fig. 6), the melting rate increases and C_r decreases until, with a coke charge equivalent to slightly less than 5 kg. of carbon per 100 kg. of iron, all the carbon is burned to carbon dioxide and none is available for reduction. In this case, the carbonaceous constituents in the effluent gases will be entirely carbon dioxide, a purely hypothetical condition when considering practical cupola operation. The connection between the melting rate per hour *(S)* and the carbon burned per hour *(C_h)* is given by the equation

$$S = 0.35W - 0.03\ C_h.$$

THE MELTING PROCESS

19. A mechanism of the process of melting in the cupola can be postulated on the basis of these observations. The iron, as it descends in the cupola, passes through a column of incandescent

coke, the height of which is completely independent of the quantity of coke charge but instead depends only upon the volume of blast. Therefore, this zone of incandescent coke is of uniform height with constant blast. Increasing the weight of coke charge causes the descending iron to require a longer period of time to reach the melting zone. Consequently the charges are retarded in their speed of descent, less iron passes through the incandescent zone per unit of time, and the melting rate is lowered. Greater melting rate is obtained by increasing the blast with a constant coke charge. The coke is burned more rapidly and the iron charges, as a result, reach the melting zone more quickly.

HEAT TRANSFER

20. Does the conception of the mechanism of cupola melting just set forth, conform with the relationships portrayed in Fig. 2? It will be recalled that the temperature of the iron can be increased in two ways (refer to pages 3 and 4). The heat requirements of the iron can either be supplied in the solid state by improved absorption from the hot gases in the cupola stack, or in the molten state by absorption from the incandescent coke as it trickles down through the combustion zone. Improved heat absorption from the hot gases by the solid iron, or better pre-heating, will result from longer periods of contact between the gases and the charges (longer elapsed time in the furnace) and should be accompanied by a lowered temperature of the waste gases. The two methods of raising the temperature of the iron by varying blast volume or coke charge may be considered separately.

The Production of Hotter Iron by Increasing the Blast with a Constant Coke Charge

21. Improved pre-heating is definitely not a factor under these conditions. The experimental results are contrary in that such conditions result in shorter elapsed times of contact (Fig. 7) and the waste gas temperature actually increases with the two heaviest coke charges (Fig. 8). The rise in temperature of the iron is apparently due entirely to heat withdrawal by the molten iron from the incandescent layer of burning coke. Under the conditions stated, the depth of the combustion zone is increased and the drops of iron must travel a longer path through an incandescent layer of coke. Consequently the temperature of the iron rises.

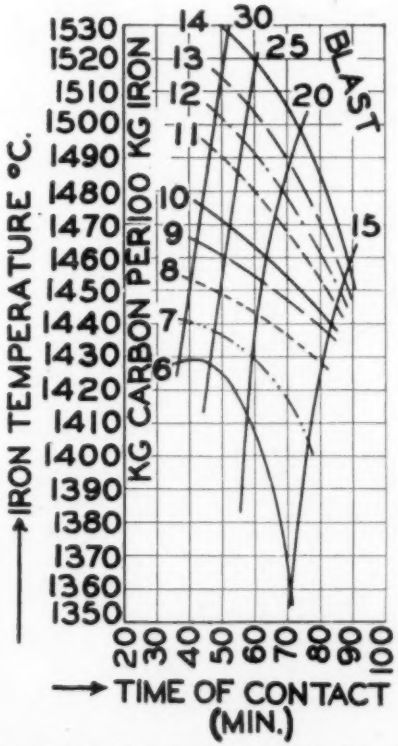

FIG. 7—RELATION BETWEEN IRON TEMPERATURE (CORRECTED), KG. OF CARBON PER 100 KG. IRON, TIME OF CONTACT BETWEEN CHARGE AND GAS, AND BLAST VOLUME.

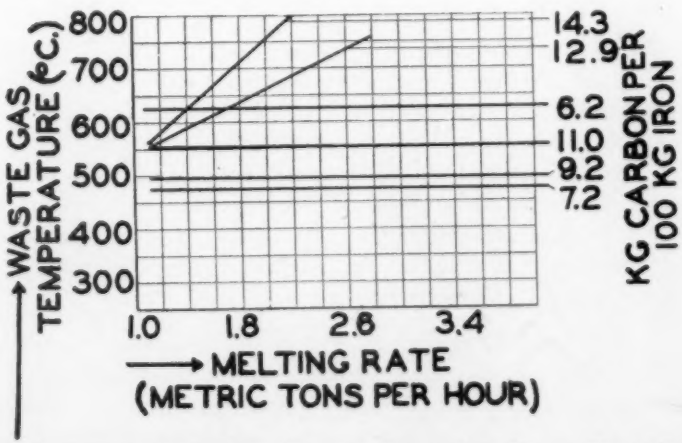

FIG. 8—TEMPERATURE OF THE WASTE GAS WITH VARIOUS COKE CHARGES (KG. OF CARBON PER 100 KG. IRON) AND MELTING RATES.

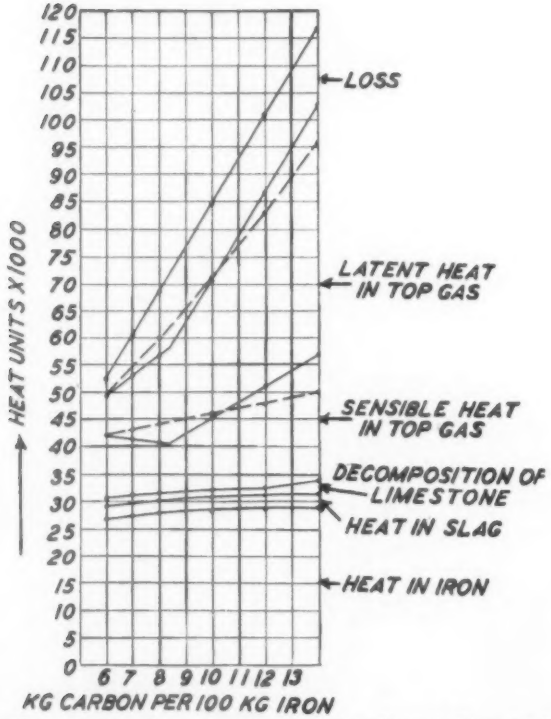

FIG. 9—HEAT BALANCE FOR A 15 CU. MTR. PER MIN. BLAST VOLUME, BASED ON 100 KG. IRON.

The Production of Hotter Iron by Increasing the Coke Charge with Constant Blast

22. Although better pre-heating (longer time of contact—Fig. 7) may produce higher metal temperatures in this instance, Jungbluth and his co-workers doubt that it does. They are of the opinion that higher iron temperatures are due to the fact that, under these conditions, a smaller quantity of iron passes through the incandescent zone in a unit of time, this zone being of uniform height with constant blast. Since the amount of heat available in this zone is more than ample in any case, the smaller quantity of iron will attain a higher temperature.

HEAT BALANCE AND THERMAL EFFICIENCY

23. Heat balances were constructed for operating conditions involving use of a constant volume of blast (Fig. 9), a constant melting rate (Fig. 10) and a constant coke charge (Fig. 11). It should be noted that when hotter iron is produced by using more

coke a poor thermal efficiency results (see Figs. 9 and 10). This fact is widely recognized. The ratio of the amount of heat absorbed by the iron to the total quantity of heat developed becomes progressively smaller with increasing coke charge. By comparison, increasing the iron temperature through the use of more blast with a constant coke charge does not appreciably affect thermal efficiency (Fig. 11).

24. Figure 12 shows the thermal relationships with various blast volumes and different weights of carbon burned per hour. The diagram is practically self-explanatory. The heat content of the iron decreases as the coke charge becomes heavier in each instance, because the metal melted per hour will decrease under such conditions. The lowering of thermal efficiency by using more coke is also portrayed.

25. Jungbluth and Stablein[7] do not think that thermal efficiency should be valued too highly as a criterion for cupola opera-

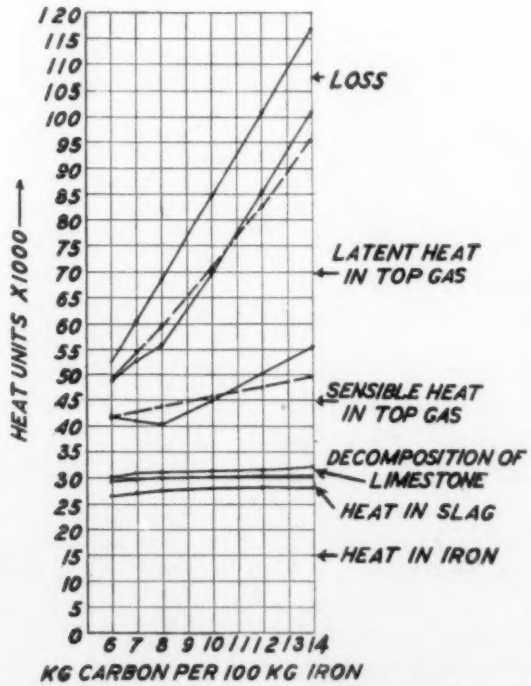

FIG. 10—HEAT BALANCE FOR A MELTING RATE OF 2 TONS PER HR., BASED ON 100 KG. IRON.

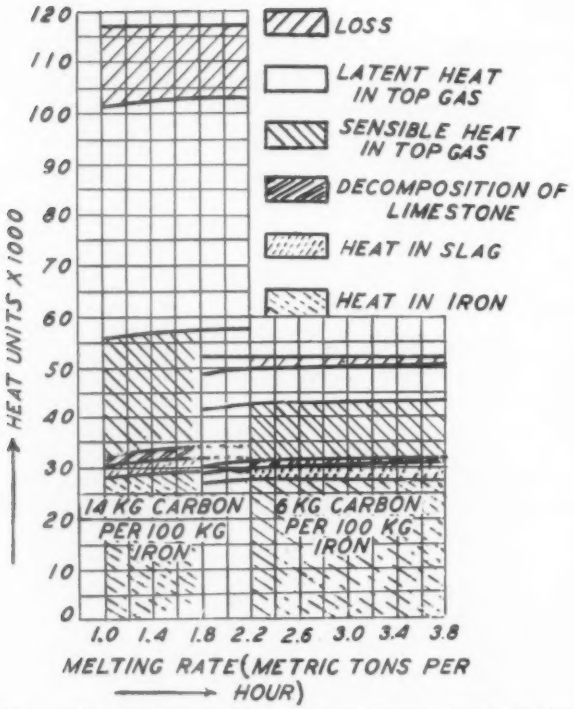

FIG. 11—HEAT BALANCE FOR 14 OR 6 KG. OF CARBON PER 100 KG. IRON, BASED ON 100 KG. IRON.

tion. They point out that sometimes it is necessary to operate with a reduced melting rate, which means operating with a fairly heavy coke charge and relatively low blast volume to obtain a requisite high iron temperature. Such conditions, of course, are associated with poor thermal efficiency. Furthermore, a consideration of thermal efficiency in itself does not give an accurate portrayal of the melting process as a whole.

26. Jungbluth and Stablein favor judging the cupola process on the basis of thermometric efficiency (n_T). Thermometric efficiency is evaluated by relating the absolute temperature of the molten iron (temperature in °C. + 275) to the melting temperature of cast iron (1145 °C. or 1420° absolute) as a reference point. Obviously, higher thermometric efficiences will be associated with hotter iron. The thermometric efficiencies are plotted in Fig. 13 for two constant blast volumes with increasing coke charge. The thermal efficiencies (n_K) are also plotted for these same conditions.

27. A study of this diagram reveals that thermometric efficiency does furnish a better picture of the cupola process than does thermal efficiency. A consideration of thermometric efficiency immediately shows the temperature of the iron increases, as was shown in the previous discussion, when the coke charge is increased while the blast is held constant. Furthermore, it reveals that, for a given coke charge, the iron temperature increases with increased blast since a higher thermometric efficiency is associated with the greater of the two blast volumes. These fundamental facts of cupola melting are not shown by a study of thermal efficiency.

Practical Considerations

28. The fact that the temperature of the iron rises with constant coke charge and increasing blast volume is attributed to the

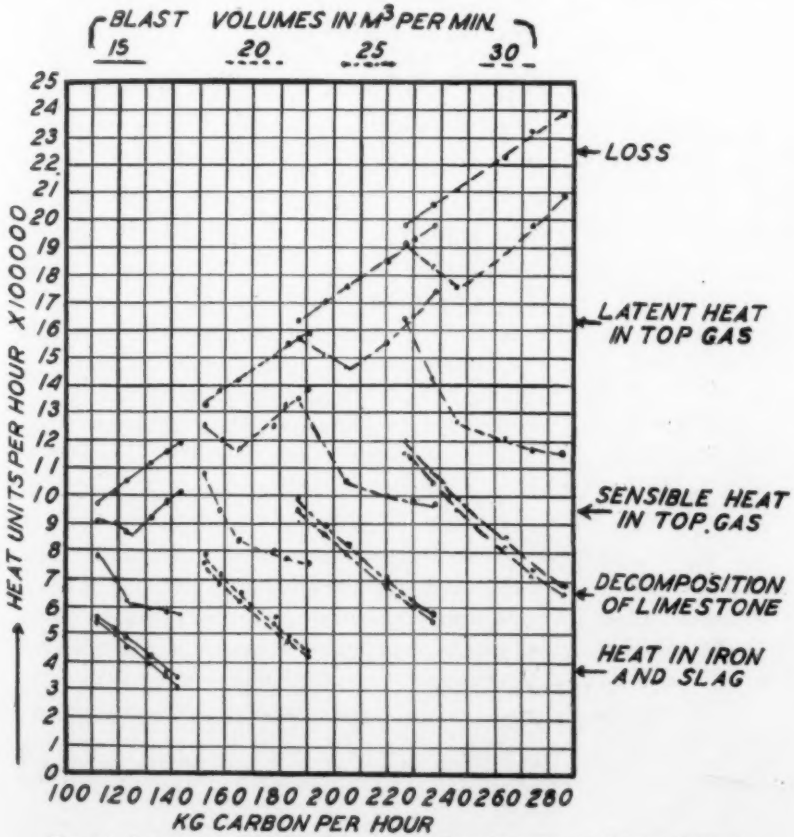
BLAST VOLUMES IN M³ PER MIN.
15
20
25
30
HEAT UNITS PER HOUR X 100000
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25
LOSS
LATENT HEAT IN TOP GAS
SENSIBLE HEAT IN TOP GAS
DECOMPOSITION OF LIMESTONE
HEAT IN IRON AND SLAG
100 120 140 160 180 200 220 240 260 280
KG CARBON PER HOUR

Fig. 12—Disposition of Heat Produced vs. The Quantity of Carbon Burned Per Hour with Different Blast Volumes.

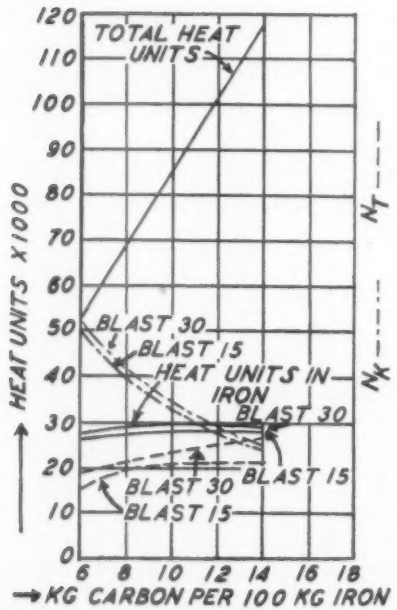

FIG. 13—THERMAL AND THERMOMETRIC EFFICIENCY OF THE CUPOLA.

increased height of the incandescent zone. Consequently, a suitable cupola construction will involve contraction of this zone to further increase its height. It has been shown that pre-heating of the cold charges in the stack of the cupola is not an important factor in determining the ultimate temperature of the molten iron. However, this is only relatively true and substantial increase in the height of the cupola can be expected to show its effect. If the effective height of the cupola is noticeably increased, no doubt all curves in Fig. 7 will be displaced to the right. An increase in the diameter will act in the same direction, but not to such a large extent.

29. Raising the temperature of the iron by holding the blast constant and increasing the coke charge results in poor thermal efficiency. Therefore, cupola operators will generally seek to obtain increased temperature of the iron by increasing the incandescent zone, that is by utilizing a greater blast volume.

30. A cupola may be considered to be "overfed" with coke only if higher temperatures are sought using heavy coke charges, that can otherwise be obtained with lighter coke charges and greater blast volume.

31. According to Jungbluth et al., there is no lack of air in

the cupola. The carbon monoxide which is present in the stack gas is not eliminated by increasing the blast, but is present as a result of the reduction of carbon dioxide by carbon in the upper coke charges. On the other hand, there is a strong possibility of excess air in cupola operation. However, if large quantities of oxygen are found in the effluent gases it is logical to first make a rigorous search for possible errors in taking gas samples and running analyses. It may be that the source of excessive oxygen in the gases lies here and not in the operation of the cupola.

32. It is quite evident that the quality, or analysis, of the iron to be melted must be given close consideration when choosing the proper method for increasing the temperature of the iron. If a low carbon, high test iron is being melted, increasing the blast is the only method available. The use of heavier coke charges leads to higher total carbon in the resulting iron. On the other hand, the coke can be increased without hesitation when melting higher total carbon iron.

33. Raising the temperature of the iron by increasing the height or diameter of the shaft is limited in scope. Increasing the height may lead to "scaffolding" or hanging of the charges in the furnace. Increasing the diameter beyond a certain dimension may lead to difficulties resulting from poor blast penetration.

34. The results obtained in these investigations naturally apply only to the conditions prevailing during this investigation, but Jungbluth and his associates believe that the hypotheses which they have constructed are applicable to all cupola operations. Furthermore, with the use of still larger quantities of blast than were used in these investigations, the curves for constant coke charges will deflect to lower temperatures since the coke will be blown cold. An indication of this will be the appearance of noticeable quantities of oxygen in the top gas, giving definite evidence of excess air. No attempt should be made to extrapolate the curves in Fig. 2 to lower melting rates, since these experiments disclosed that considerable difficulties occurred with low coke charges and low blast volumes because of scaffolding of the charges.

35. Thermal efficiency should not be considered as representing the sole criterion for evaluating cupola operation. Sometimes a low melting rate is required, which necessitates operating with a poor thermal efficiency to produce hot iron.

SUMMARY

36. The following hypothesis of operation was constructed to describe cupola melting: The blast introduced into the cupola burns the carbon in front of the tuyeres almost completely to carbon dioxide. The height of the zone of incandescence, therefore, is independent of the coke charge, and depends only upon the volume of blast used. Therefore, the incandescent zone is of uniform height with constant blast volume. A faster melting rate with constant coke charge and increasing blast volume results from the higher zone of incandescent coke associated with these conditions, and more coke burning in unit time making it possible for the charges to descend more rapidly.

37. With constant blast and increasing coke charge, the added coke does not burn in the incandescent zone but only serves to reduce part of the carbon dioxide formed in this zone to carbon monoxide. As the coke charge is increased, greater quantities of this "surplus coke" must be removed before the charges can reach the incandescent zone, and a reduction in the rate of melting occurs.

38. An investigation of the temperature of the resulting iron and the construction of heat balances indicated that the hypothesis of operation developed is in agreement with the thermal data.

Appendix

Mathematical Treatment of Cupola Melting

G. Buzek,[8] as early as 1910, showed that the melting rate could be expressed mathematically in terms of the blast volume, coke charge, and the air consumed per kilogram (2.2 lb.) of carbon as:

$$(1) \qquad S = 600 \times \frac{W}{L \times K \times k} \text{ wherein,}$$

S = the quantity of iron melted per hour in metric tons (1 metric ton = 1000 kg. = 2200 lb.),

W = the volume of blast per minute in m^3 (1 cu. mtr. = 35.29 cu. ft.),

L = the quantity of air consumed per kilogram (2.2 lb.) of carbon in cubic meters,

K = the quantity of coke in kilograms used for melting per 100 kilograms of iron, and

k = the quantity of carbon contained in 100 kilograms of coke (per cent carbon in coke x 100).

In this equation the number "600" represents a simple weight and time conversion.

The quantity of air actually consumed per kilogram of carbon *(L)* can be computed if the percentages of carbon dioxide and carbon monoxide in the effluent gas are known. The ratio of the percentage of carbon dioxide in the gases to the total percentage of carbon bearing gases, that is the carbon dioxide plus the carbon monoxide, multiplied by 100 is designated as n_v so that

$$(2) \qquad n_v = \frac{\%CO_2}{\%CO_2 + \%CO} \times 100.$$

Therefore, the value "n_v" may be considered as an index of the stage of combustion. If the volume of air required for combustion of one kilogram of carbon is plotted against the value of n_v for all stages of combustion from 100 per cent CO ($n_v = 0$) to 100 per cent CO_2 ($n_v = 100$), Fig. 14 will be obtained. The equation for the straight line relation in this diagram shows that

$$(3) \qquad L = 4.45 \times \frac{(100 + n_v)}{100}.$$

Returning for a moment to consideration of equation (1), it is noted that L appears in it. Making use of equation (3), a substitution may be made in equation (1) for L in terms of n_v. When this is done the following equation results:

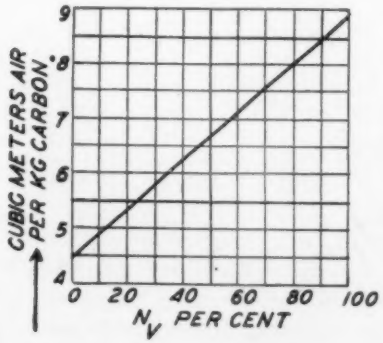

FIG. 14--RELATION BETWEEN N_V AND AIR REQUIRED FOR THE COMBUSTION OF 1 KG. OF CARBON TO CO_2 OR CO.

$$(4) \qquad S = \frac{60}{10} \times \frac{W}{\frac{K \times k}{100} \times 4.45 \times \frac{100 + n_v}{100}}.$$

By arithmetical manipulation this yields the next form:

$$(4a) \qquad S = \frac{60{,}000W}{K \times k \times 4.45\ (100 + n_v)}.$$

This equation has long been accepted at face value. A part of this investigation sought to clarify the relationships that might exist between the various factors on the right hand side of equation (4). What effect will a change in any of these variables have on S as well as the other factors in the equation? According to these investigators there is no connection between the blast volume *(W)* and the coke charge, or the kilograms of carbon consumed per 100 kilograms of iron $\left(\frac{K \times k}{100}\right)$, since they can be changed independently of one another.

Furthermore, Jungbluth, Heller and Korschan believe that, with a constant coke charge, no relation exists between blast volume *(W)* and composition of the stack gas as represented by n_v. This would mean that the percentages of carbon dioxide and carbon monoxide in the stack gases do not change as blast volume is varied. In this they are supported by W. Hollinderbaumer[9] "within certain limits" and by E. Piwowarsky and F. Meyer[10] "with accurately measured coke charges and increasing blast volume." With constant coke charges and increasing blast volume, therefore, a purely linear relationship exists between melting rate and blast volume as shown in Fig. 15.

If n_v also remained constant with constant blast and increasing coke charges, then the melting rates would be inversely proportional to the coke charges. A close inspection of Fig. 15 reveals that this is not the case. Rather, as the coke charge is increased the melting rates are somewhat greater than would correspond to the inverse proportionality. A consideration of equation (4) shows that this is only possible if n_v decreases as the coke charge becomes heavier. Therefore, there is actually a connection between the coke charge and n_v. It is further evident from equation (4) that, with a knowledge of melting rate, blast volume, and coke charge, the

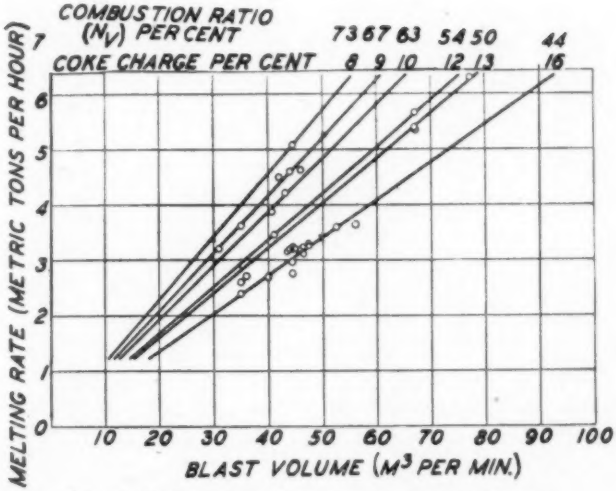
COMBUSTION RATIO
(Nv) PER CENT
7 3 6 7 6 3 5 4 5 0 4 4
COKE CHARGE PER CENT
8 9 10 12 13 16
MELTING RATE (METRIC TONS PER HOUR)
0 1 2 3 4 5 6 7
10 20 30 40 50 60 70 80 90 100
BLAST VOLUME (M3 PER MIN.)

FIG. 15—MELTING RATE, COKE CHARGE AND BLAST VOLUME.

relation between coke charge and n_v can be calculated. Systematic investigations by Jungbluth, Heller and Korschan permitted plotting of this relation (please refer to Fig. 3). This curve, which has been called the n_v curve, is claimed by Jungbluth and Korschan to be the fundamental law that controls the entire cupola process.

The relation can be stated mathematically as:

$$(5) \qquad n_v = \frac{386.5}{\frac{K \times k}{100}} + 15$$

In view of the importance of this relation, an investigation was made to ascertain if it is quite generally applicable or varied by other influences. According to Jungbluth and Bruhl[11], with due consideration to the deviations to be expected in experiments of this type, the diameter of the cupola is without effect on the course of the curve, at least for furnaces with diameters between 23½ and 51 in. (600 to 1300 mm.). A. Nahoczky[12] is also of the opinion that furnace diameter does not play an essential role.

Recently, G. Buzek and M. Czyzewski[13] investigated the influence of coke size on coke consumption in the cupola. From this investigation, information is available relative to the influence of coke size on n_v. The coke charge used was equivalent to 18.7 lb.

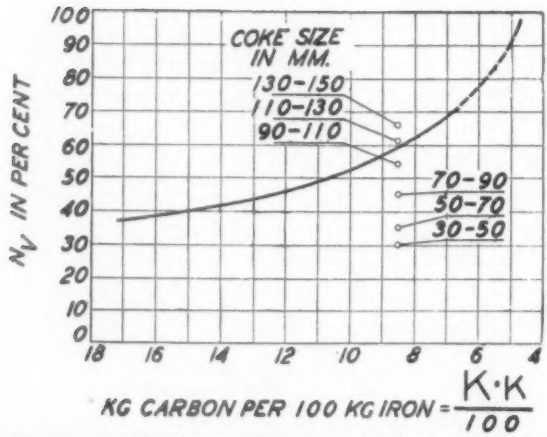

FIG. 16—INFLUENCE OF COKE SIZE UPON N_V (AFTER G. BUZEK AND M. CZYZEWSKI).

of carbon per 220 lb. of iron (8.5 kg. C/100 kg. iron), and the sizes lie between 1.2 and 5.9 in. (30 and 150 mm.). The values of n_v as computed from the original diagrams are plotted in Fig. 16. From this diagram it is immediately apparent that n_v definitely depends upon the size of the coke. Therefore equation (5) is not generally valid but is dependent upon this variable. It will be noted that the curve in Fig. 16, which originates from Jungbluth's and Korschan's work, with coke of about 4.33 in. (110 mm.)

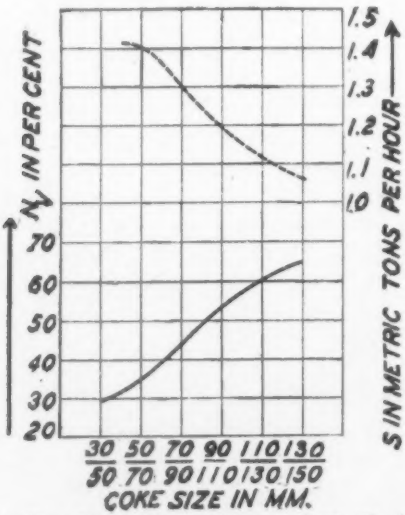

FIG. 17—INFLUENCE OF COKE SIZE ON N_V AND MELTING RATE (S). (AFTER G. BUZEK AND M. CZYZEWSKI.)

diameter and 7.08 to 7.87 in. (180 to 200 mm.) length, passes between Buzek's and Czyzewski's points for coke sizes of 3.54 to 4.33 in. (90 to 110 mm.) and 4.33 to 5.12 in. (110 to 130 mm.). This indicates good agreement between these investigators.

In the same investigation by Buzek and Czyzewski, it was established that, with a constant coke charge and blast volume, an increase in melting rate is observed with decreasing coke size and thus with decreasing n_v (Fig. 17). This would be expected, since, with a fixed coke charge and blast, the smaller coke sizes will burn more rapidly, presenting an increased surface area for reactions.

The elapsed time from charging to tapping is also strongly influenced by n_v. Doubling the coke charge, which will cause a decrease in n_v, results in an increase of only about 30 per cent in the elapsed time. On the other hand, when blast and coke charge, hence n_v, are held constant and the weight per unit volume of the iron in the charge is doubled, by reducing the size of the pieces in the charge, the elapsed time required for a charge to pass through the cupola will increase by 55 per cent.

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DISCUSSION

Presiding: W. H. SPENCER, Thomas Foundries, Inc., Birmingham, Ala.

FRANK J. DOST:[1] At what point above the tuyeres does your stack analysis reach a point of equilibrium, or at which point would you take gas samples to get the analysis?

MR. MASSARI: Preferably in the fusion zone because the things that happen in the fusion zone itself affect the behavior of the cupola the most. From a purely practical standpoint however, the futility of taking samples from this location can be realized. Any sampling tube that is inserted in the cupola and exposed to the temperatures existing in the fusion zone would either fuse shut, or slag or iron would get into it and plug it up.

We took gas samples at a point approximately 3 ft. below the normal level of the charges in the cupola in our experiments; the reason being to prevent an infiltration of air from the atmosphere at the charging doors. At this location the analysis of the gases reflects what is happening in the fusion zone because naturally a change of composition of the gas in the fusion zone will be reflected in a change at the sampling point.

[1] Supt., Sterling Foundry Co., Wellington, O.

MR. DOST: Do you then concur with the authors of these papers that you translated that there is a point of equilibrium some place?

MR. MASSARI: Yes, but it is a function of the time that the gases have to attain equilibrium in their ascent as well as the temperature existing at that location. There will be a different equilibrium at different heights; and to use the composition of the gases as an index of the behavior of the cupola, it will be necessary to arbitrarily select a location for sampling that is practical.

After having once established what is considered to be a good operation, the analysis at the sampling location should be observed and then adhered to as closely as possible. Whether the composition happens to be 14 or 10 per cent carbon dioxide, if that proves to be the operating optimum and results in the best grade of iron for the castings being produced, then naturally that is the composition to adhere to.

MR. DOST: In regard to carbon dioxide percentage; in your own work have you determined an amount of CO_2 that would represent the most satisfactory melting operation?

MR. MASSARI: Yes, but it will vary, dependent upon whether the operation is hot or cold blast. A cold blast cupola can be operated with 14 per cent carbon dioxide in the effluent gas, but on a hot blast installation the carbon dioxide content must be maintained around 12 per cent.

MR. DOST: In our operation we take gas samples for analysis about 10 ft. above the tuyeres and about 8 ft. below the charging door. This is about half way up the cupola and we do have trouble with the sampling tubes being closed by slag.

MR. MASSARI: I would suggest that you raise the location of the tubes and then modify your conception of what the gas analysis should be.

The gas will be higher in carbon dioxide and lower in carbon monoxide, the higher above the fusion zone the samples are taken. The reason is that the carbon dioxide-carbon monoxide ratio is a function of temperature. Carbon dioxide in contact with an excess of coke will attain an equilibrium due almost entirely to temperature.

Higher temperatures will result in higher percentages of carbon monoxide and lower carbon dioxide. For that reason, as the gas ascends higher and higher in the stack, the temperature is naturally becoming lower and the dioxide percentage is increasing, while the monoxide percentage is decreasing. This is a well established fact, of course; a fact that good gas producer operations are entirely based upon.

FULTON HOLTBY:[2] We are doing some test work at the University of Minnesota, at the present time, taking gas samples at five different points up the stack of a 15-in. test cupola.

[2] Asst. Prof., University of Minnesota, Minneapolis, Minn.

These five different points where we draw off the gas samples represent the position of the five metal charges in the cupola including the one in the melting zone. The first tap point would be about 28-in. above the tuyeres and each tap point 12-in. above that point. We found that the first tap point 28-in. above the top of the tuyeres, would be quite variable in a CO_2 analysis during the heat, especially if we are trying to maintain constant control. The next three tap points, above the first point, gave very uniform analysis. The first tap point would vary widely from the second tap point, but the second, third and fourth tap points would be all about the same analysis. The fifth tap point, the one right underneath the charging door also would vary widely from tap points two, three and four.

Mr. Massari did you say that as the coke size decreased, the CO_2 content would decrease—the carbon dioxide decreases and carbon monoxide increases.

MR. MASSARI: I do not recall having made that statement regarding temperature. It is true, however, that it was found that as the coke size decreased the amount of carbon monoxide increased and the melting rate also increased.

MR. HOLTBY: That is exactly opposite from what we have found on our test work at the University of Minnesota.

MR. MASSARI: The reason I took specific pains to make a point of the rather large coke size that they used in this comparatively small cupola is that the size of the coke is not compatible with the size of the cupola. I am to a considerable degree skeptical of some of the deductions that they made.

MR. HOLTBY: Our cupola is 15-in. and we use coke sizes from 1-in. to 4-in. for our test work. We have found that in the small size coke, 1¼-in. to 2-in., we cannot get our carbon dioxide much over eleven per cent. The temperature of the iron is low and we have considerable trouble from slag. At the present time, we find that 2½-in. to 3-in. coke is the best for that size cupola. That gives us about 14 per cent CO_2 throughout the heat with a minimum amount of silicon loss and high metal temperatures. When we use the 3½, 4, and even 4½-in., coke it is very difficult to keep the cupola below 16 per cent CO_2 in what I have described as station No. 3, for the tapping of the gas. We have checked this at several local foundries near the university. One foundry had started out with a 48-in. cupola using the 4-in. coke and we finally persuaded them to try the 3-in. coke which gave very good results and less loss of silicon and manganese, higher metal temperature, and very little slagging trouble. However, unbeknown to us, they tried to use a 2½-in. coke and immediately ran into trouble. The fact is they lost the heat, the slag froze, and the temperature of the iron went down.

R. H. WATSON:[3] At one of the cupola malleable plants, we had a CO_2 mechanical recorder and when we tried to operate this cupola by controlling, keeping the pen on the 14½ per cent CO_2 mark, the iron ran 1.05 to 1.10 per cent silicon, and that seemed to be an excellent proposition as regards the analysis. I do not believe in a variable blast on a cupola, but in this case we operated three months this way and we had excellent results. We did this by increasing and decreasing the volume of the blast.

MR. MASSARI: I am very glad to hear that, but I do not know that I can wholly agree with the statement that there is an objection to varying the blast volume in operating the cupola. I agree there is a definite objection to ignorantly varying the blast volume, but intelligent varying of blast volume is highly profitable. A good deal of the variation in composition of iron issuing from a cupola is due to a variation in the stage of combustion in that cupola. If the cupola is operated at excessively high stages of combustion, namely, with high percentage of carbon dioxide in the effluent gases, a higher loss of silicon and manganese is the invariable result. With a constant gross amount of silicon and manganese going into the cupola, our hopeful anticipation is that we will have a constant loss of silicon and manganese. With variation in the stage of combustion, a variable loss will result and along with it the inherent troubles that are due to variation in analysis of the issuing iron.

MR. WATSON: I would like to say a few words regarding carbon pick-up from coke. I have found in the past 4 or 5 years that, regardless of coke size, a coke whose ash analyses 25 per cent alumina will supply much less carbon pick-up.

MR. DOST: In considering the feasibility of varying the air supply, you said "air volume," not air weight. If you were compensating for temperature and barometer, would you consider that the same as varying the weight of the air?

MR. MASSARI: Yes. There is still another factor that must be taken into account, namely, that the amount of air entering the cupola cannot be varied over very short time intervals. The cupola is a large piece of equipment and consequently there is an inertia factor to be considered. The response to a change in the amount of air entering the cupola is rather slow. In a 75-in. cupola, I think it might be safely stated that a change does not evidence itself much short of 15 to 20 minutes. As a consequence, it is neither sensible nor practical to fluctuate the amounts of air entering a cupola in the same manner as the amount of air being fed to an installation that shows an immediate response, such as an oil or gas burner.

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[3] Metallurgist, Hanna Furnace Corp., Detroit, Mich.

HENRY C. SEIDEL:[4] Here in the paper the authors made the point that the temperature could be raised either by increasing the coke or by increasing the blast. I would like to hear some comments about how that could be applied to the regular cupola and something about the type of coke.

MR. MASSARI: It is very evident, of course, that such variations in operation can only be made within certain limits. If the same amount of fuel is used and the amount of air furnished to burn that fuel is increased, a higher stage of combustion will obviously be attained. A greater percentage of the total potential heat in the fuel will be made available as a result. That is one method of raising the temperature. The other method is by extravagant use of fuel whereby the total amount of fuel available is actually increased in relation to the amount of iron that has to be melted. The latter can only be done within certain limits since a point is finally reached where the cupola will be choked with fuel. Disastrous results may occur as a consequence of increasing the air for a given amount of fuel in an effort to attain higher stages of combustion. The tendency to carry this too far will be evidenced by the fickle behavior of the cupola, the inability to maintain uniform composition, and an excessive loss of silicon and manganese. I wish to point out again that a desire to attain higher melting temperatures and melting rates through increasing the blast volume and burning to higher stages of combustion represents false economy. As a result of the higher stages of combustion, the loss of silicon and manganese will increase very rapidly during melting and this loss represents a costlier operation since these elements cost a good deal more than coke.

L. G. ROBINSON[5] *(Written Discussion):* This summary of a series of articles by Jungbluth et al, should be of much value to foundrymen and metallurgists in this country, inasmuch as the general trend of the investigations made is very clearly indicated. Cupola operation and control by the carbon dioxide percentage in the effluent gases is not far off. In only one of these articles, Jungbluth and Heller; is there any reference to the tuyere size used, in the particular cupola in which the investigations were made. The tuyere size in this particular investigation ranges from a ratio of 1:35, to 1:12, in a 21½-in. diameter cupola. It would seem evident that such tuyere size would make questionable any conclusions derived from the investigations. Unfortunately, most of the conclusions deduced are from tests made with apparently no consideration given to the coke size and evidently the Germans do not consider the reactivity of the coke as of much importance.

The authors have some difficulty in explaining why more air with the same coke charge gives hotter iron. This is easily explained if it is assumed that the tuyere size remained constant. With each increase in air, there is also an increase in the velocity of the air through the

[4] Mgr., Penn Rillton Co., New York, N. Y.
[5] Louis G. Robinson Labs., Cincinnati, O.

same size tuyeres. This increase in velocity is sufficient to explain the increased temperature obtained with a constant coke charge and increased air. It is possible to obtain higher temperatures with the same coke charge and the same air by increasing the velocity of the air entering the cupola.

It is unfortunate also that a new ratio, "N_v" is introduced into the foundry nomenclature. There are too many valueless ratios now. The old ones like coke ratio and tuyere ratio are misleading in themselves. This "N_v" which is the ratio between carbon dioxide and the carbon dioxide plus the carbon monoxide is simply unnecessary and confusing. The value of this factor depends on the carbon dioxide, because the carbon monoxide itself is dependent on the carbon dioxide. If the carbon dioxide value be substituted for the value of "N_v" in the diagrams shown in this paper, a much clearer picture will present itself.

The most serious criticism of this series of papers is a lack of consideration of the velocity of the air entering the cupola, and it is expected that, when air velocity is given due consideration in future research, a great many of the conclusions drawn, will at least be modified.

R. A. CLARK[6] *(Written Discussion):* Every foundryman is interested in obtaining the best possible coke ratio consistent with the necessary metal temperature and quality of metal. This paper has been undoubtedly carefully studied by many with a view to improving their cupola operation. The translators have done a service to the American foundry industry in making available for study the experiments of Europeans on this subject.

The main conclusion to be drawn from this paper would seem to be that with increasing blast volumes and constant coke charge, the temperature of the iron melted will increase due to increase of the height of the incandescent layer of burning coke. This is due to the longer path of the drops of molten iron through the white hot coke bed. Such conclusions are thoroughly justified by the results obtained in these experiments. However, if the blast volume had been increased beyond the figures used in these experiments, I believe that eventually the temperature of the metal at the spout would be formed to decrease with increasing volume. The authors recognize these limitations in paragraph 34. The critical blast volume at which such a decrease would begin to take place would, I believe, upon further investigation be found to vary with the burning rate of the coke used as influenced by size of individual pieces and general structure. In other words, at some unknown blast volume, varying with the coke used, the blast would begin to blow the coke out rather than increase the intensity of combustion.

The critical blast volume at which this would take place would also be influenced by the contours of the cupola lining (whether boshed

[6] Metallurgist, Lakey Foundry & Machine Co., Muskegon, Mich.

or straight), the amount of preheating obtained as influenced by shaft height and diameter, and the tuyere design (whether auxiliary tuyeres were used and their location and amount of air passed through them). Thinking along this line, it would seem that the best coke ratio could only be obtained by balancing the burning rate of the coke in the sizes charged with blast volume and cupola dimensions to obtain the highest possible operating bed without blowing a high enough blast volume to chill the tuyere area. As we have no accepted method of determining burning rate of a coke in cupola sizes, this can only be done by trial and error and is a tedious and expensive process.

MESSRS. MASSARI AND LINDSAY *(Reply to Written Discussions)*: The authors wish to reiterate that the views expressed in this paper are not their own and they are not necessarily in accord with all of them. They wish to express their thanks to all those who have contributed to the discussion since by such discussion attention is focused on the salient features of the paper and further work on controversial points may be stimulated.

The authors wish to thank Mr. Clark for his comments. The writers agree that the method of raising iron temperature by increasing the blast volume can be carried too far, as Mr. Clark has mentioned.

Mr. Robinson points out that the German investigators have not given much attention to coke size. We cannot say whether or not the coke size was maintained approximately constant in these investigations. However, it is apparent that the effect of coke size is recognized if we refer to the latter portion of the appendix (see Figs. 16 and 17). It is apparent as commented upon by Mr. Robinson that tuyere ratio, and hence blast velocity, would have an important bearing on the results of such an investigation.

Some Observations in the Duplexing of Malleable Iron

By G. A. Schumacher*, Albion, Mich.

Abstract

While the author admits that the control of slag in the cupola-air furnace duplexing process is not new, he presents some very interesting data to show the effect of such control. He points out, from a practical standpoint, that it has been his observation that proper slag manipulation has facilitated the control of carbon, silicon and manganese, reduced refractory costs and has produced a metal which does not misrun and hot tear easily.

1. In presenting the data submitted in this article, the author wishes to admit that the material is not new in melting circles. The informaion is submitted in the hope that it will stimulate discussion involving an exchange of ideas through which everyone will be mutually benefited.

2. From a metallurgical viewpoint, data will be given indicating the results which synthetic slag control and selective raw material produced in facilitating composition control in malleable duplexing, increased refractory life and a lowering of hard iron scrap attributed to hot tears and misruns.

3. In a previous article[1], the author described the melting unit consisting of cupola-air furnace duplexing, components of the cupola charge used at that time, chemical composition of the metal, temperature characteristics, construction of the air furnace

* Chief Metallurgist, Albion Malleable Iron Company.

[1] Schumacher, G. A., "*Duplexing Malleable Cast Iron*," The Foundry, vol. 66, p. 22. (October, 1939).

Note: This paper was presented before a Malleable session at the 45th Annual A.F.A. Convention, New York City, N. Y., May 13, 1941.

(holding furnace), annealing practice, and mechanical properties of the product being produced.

4. The current productive program has demanded 18 hours of continuous pouring from the furnaces; the cupolas must be dropped in time to be repaired and suitably restored for operation the following day; the metal poured must meet chemical specifications and founding requirements relative to fluidity and checking.

Refractory Consumption

5. The air furnaces are used alternately, and considerable care and inspection are necessary to assure extended periods of operation with minor repairs. As a result of the firing and slag control program, a 2 year refractory consumption record is as follows:

0.67 Bung brick consumed per ton of metal poured.
1.28 bottom brick consumed per ton of metal poured.
2.84 sidewall brick consumed per ton of metal poured.

6. Included in the above figures are several short-lived brick bottoms in these furnaces. These early failures of the bottoms were one of the primary causes leading to slag control, which not only prevented the oxides of iron normally concentrated in the slag from attacking the bottom brick, but also minimized and often eliminated the necessity of adjusting the composition of the bath with additions of carbon, silicon, and manganese.

Slag Functions

7. The function of slag is to act as a collector of inclusions or nonmetallic impurities in the bath such as oxides of silicon, manganese, and iron, as well as silicates, manganese sulphide, etc. The slag also may act to protect the liquid metal from the contaminating influence of the flame, and to control the reaction rates in the bath, principally oxidation.

8. In steel melting practice, it is well known that the higher the iron oxide in the slag over a heat of steel, the greater will be the amount of iron oxide in the molten steel under equilibrium conditions. The higher the iron oxide in a heat of white cast iron, the greater is the reaction rate in eliminating carbon, silicon, and manganese from the bath.

9. The term "slag control," in this discussion, refers to the

practice of diluting the concentration of iron oxide in the slag normally formed in air-furnace practice by additions to the bath of limestone and silica sand. The usual amounts of these constituents added to the slag per hour are 20-lb. of limestone and 60-lb. of sand.

Slag Addition Data

10. The following data from actual practice will serve to demonstrate the practice followed in the metal preparation.

11. A 10-ton cold charge is melted down in the air-furnace at the beginning of each day's run. To this charge is added 250 to 800-lb. of sand, the actual amount depending upon the iron oxide content of the slag at the end of the last heat made. A typical day of slag additions is given in Table 1.

Table 1

TYPICAL DAILY SLAG ADDITIONS

Time	*Iron Oxide Content in Slag, per cent*	*Slag Additions*	*Analysis of Metal, per cent* C.	Si.	Mn.	S.
5:30 A.M.	11.6	300 lb. sand with 10-ton cold charge	2.61	1.05	0.44	0.138
7:00	10.02		2.55	1.08	0.43	0.141
9:30	12.48	320 lb. sand and	2.58	1.06	0.46	0.149
11:30	11.6	120 lb. limestone	2.56	1.09	0.45	0.151
2:30 P.M.	10.45		2.61	1.07	0.46	0.149
5:30	8.60	30 lb. sand and	2.57	1.11	0.45	0.149
9:30	10.30	10 lb. limestone	2.56	1.05	0.46	0.150
11:00	4.58	every half hour	2.52	1.12	0.45	0.151

12. The cupola was dropped at 8:18 P.M. There were 28 tons of iron in the holding furnace at that time. The operator reduced the flame temperature 90°, as recorded by an optical pyrometer, and the iron temperature remained at 2,880° F.

13. No additions of petroleum coke, ferrosilicon or ferromanganese, were made to the above heat after the cupola was dropped. The furnace was stopped at 12:05 A.M.

Method of Slag Analysis

14. Method of slag analysis used is as follows:

1. Dissolve 0.5 grams in 15 cc. HCl.
2. In 4 minutes add 10 cc. HNO_3.

3. In few minutes add 2 cc. HF.
4. Evaporate to dryness.
5. Add 10 cc. HCl.
6. When salts are in solution, wash down breaker and watchglass.
7. Reduce iron (to colorless solution) with $SnCl_2$.
8. Dilute and cool.
9. Add 15 cc. $HgCl_2$.
10. Titrate with $K_2Cr_2O_7$ until one drop of solution will not change the color of one drop of a 1 per cent solution of $K_3Fe(CN)_6$.
11. Calculation:

FeO = cc. of $K_2Cr_2O_7 \times 0.56 \times 1.28 \times 2$.

Preparation of Solutions

15. Standard solutions are prepared as follows:
    1. 1/10 N. $K_2Cr_2O_7$: made by dissolving 4.913 grams to 1 liter.
    2. $SnCl_2$: (a) 30 grams dissolved in 100 cc. HCl.
       (b) add 100 cc. H_2O.
    3. $HgCl_2$: saturated solution.
    4. $K_3Fe(CN)_6$ (1 per cent solution): 1 gram in 100 cc. of H_2O.

Observations on Day's Run without Slag Control

16. A typical day without synthetic slag control gave iron oxide contents of slag as follows:

Time	*FeO in Slag, per cent*
5:00 A.M.	20.3
9:00	18.1
11:00	18.7
3:00 P.M.	18.7
6:00	20.6
9:10	20.4
11:30	23.2

17. No sand or limestone was used throughout the day. Considerable difficulty was experienced in maintaining the carbon, silicon, and manganese as many and varied additions of these elements were necessary. The slag on this bath was very active (frothy).

Effect of Slag Control on Refractory Life

18. By maintaining a synthetic slag, which is low in FeO content, the life of the brick bottoms to first patch has been increased from 1,600 tons of iron to 2,700 tons of iron.

19. Obviously, if during the day or at the end of cupola melting the iron comes so high in carbon, silicon, and manganese that the ordinary rate of oxidation in the holding furnace will not produce white iron in the range, then the slag has to be skimmed off, suitable steps taken to regain proper composition, and a new slagging operation is begun.

Influence of Charge on Product

20. It is the author's opinion that the iron oxide content in the slag in the holding furnace is a function of the type of charge entering the cupola. It often has been observed that with a high percentage of rusty steel and rusty malleable in the cupola charge, an iron is produced at the spout which, though high in carbon and silicon, lacks flowing power in the mold. For example, a charge may consist of:

	Per Cent
Silvery pig	5
Sprue remelt	50
Railroad malleable	10
No. 1 steel scrap	20
Rails	15
	100

21. The railroad malleable and No. 1 steel scrap may be very rusty. The castings produced from the above mix are very sensitive to hot tears, and a considerable number of misruns are produced owing to the quick-setting tendency of this metal. Daily graphs indicate that, on an average, 15 to 20 per cent of our total hard iron rejections are caused by hot tears in the castings.

22. Current production schedules dictate a melting speed so rapid through the duplexing unit that the harmful effect of high iron oxide content in the cupola charge cannot be overcome by synthetic slagging practice. Apparently, sufficient time for iron oxide removal from the bath is not available. It was, therefore, necessary to produce a metal from component cupola charges which introduced lower oxide contents. At present, the nature of cupola charge is as follows:

	Per Cent
Silvery pig	5
Malleable pig	5
Sprues	50
Bundled steel	20
Rails	15
Malleable scrap	5
	100

23. The iron oxide content in slags formed over this bath in the air furnace, without synthetic slag additions, resulted in only 14 per cent iron oxide as compared to 20 per cent in previous practice.

24. As a further result of the change made in the cupola charge, there appears to be a very definite reduction of hot tears in the hard iron scrap. The iron appears to have better flowing power, as determined by the A. F. A. spiral test.

25. Sand and limestone additions are continued even though the nature of the charge, with regard to lowering the material high in iron oxide, is being corrected. Air-furnace slags above 20 per cent iron oxide are very active slags. Slags below 10 per cent permit closer composition control in the bath.

CONCLUSIONS

26. In conclusion, the practice of slag control, that is, the dilution of iron oxide content of slag in the air-furnace by limestone and sand additions has:

1. Facilitated the control of carbon, silicon, and manganese.

2. Reduced refractory costs, especially bottom brick which are slowly destroyed by high iron oxide slags.

27. The author believes that the elimination of materials high in iron oxide content is the preventative means of producing a metal which will not misrun and hot tear easily.

ACKNOWLEDGMENTS

28. The author acknowledges the assistance rendered him in this work by E. J. Ash, Associate Professor of Metal Processing, University of Michigan, Ann Arbor, Mich.

DISCUSSION

Presiding: JOHN WAGNER, Wagner Malleable Iron Co., Decatur, Ill.

MEMBER: Last October, we started to study slags, not primarily with the idea of analysis control, but with the idea of cutting down the iron oxide content of the slag and trying to save our brick bottoms.

Our practice in a furnace that held approximately 10 to 15 tons when it was full, was to put 175 lb. of sand in the night before. We ran slag analyses after every hour and I thought that the results we got, using the 175 lb. of sand, might be interesting.

We started pouring at 7 o'clock in the morning. At that time, the cupola had run approximately 2 hr. and we had a bath of a little over 11 tons in the furnace. At 8:30, the iron oxide content of the slag was 12.69 per cent. As the slag was being diluted, the iron oxide content dropped down to 5.50 per cent at 12:30, and started to climb again when skimming proceeded, and reached a peak of 67.5 per cent. The next day we decided to cut out the sand and our iron oxide content at 9:30 had arisen from 10 to 15 per cent; this is not absolutely correct mathematically. We do not know what the conditions might have been at 9:30 for 9:30, but it does show an upward trend in iron oxide content. We cut the sand out because it made an undue amount of slag and we thought that we were losing thermal efficiency. As time went on we did notice that under certain conditions, the carbon was rising and the silicon was dropping, which led us to believe that that slag must be definitely oxidizing.

We did not do very much work after that, but I am glad to hear that Mr. Schumacher has gotten out of the rut that malleable foundrymen have been traveling. That is, considering slag as a nuisance and just skimming it off when we had too much of it. Instead of studying the slag, we just got rid of it. The steel maker does not do that. I think if we all worked on a problem of that nature, in trying to control the slag, we would find a solution. Skimming is a nuisance, and as you begin to climb up in temperature, as you do in the duplex, you do corrode your brick work a good deal more than you do on commissions of batch melting.

C. F. JOSEPH[1]: We have duplexed iron since 1926. At that time, we started with a coke which burned very rapidly. I think the iron oxide content of our cupola slag ran around 18 to 21 per cent, and the slag was black and green, but mostly black because of the high iron oxide content. The castings produced used to crack and shrink a lot worse than they did when we melted the iron in the air furnace. At that time, we ran the total carbon and silicon around 3.60 to 3.80 per cent. As time went on, we changed our coke and we got a coke which burned very slowly. We used a lot more coke in our cupola, and the iron oxide content of the cupola slag dropped as low as 4 to 6 per cent. Castings

[1]Chief Metallurgist, Saginaw Malleable Iron Div., General Motors Corp., Saginaw, Michigan.

produced from a slag around 4 to 6 per cent iron oxide cracked far less than the castings produced with the iron oxide content around 18 to 21 per cent.

Recently, we have used a coke mixture, using some beehive coke with the slow-burning coke, and the iron oxide content of the cupola slag again went up around 9 to 13 per cent, and again the castings started to crack more than they did with the iron oxide content lower.

I brought this out to show that the iron oxide content of the cupola slag has a direct bearing on shrinks, cracks, and fluidity. We have tried to correlate the color of the cupola slag with the iron oxide content, but found that we could not get any definite relation for the simple reason that the material going into the cupola will vary at times from clean sprue to dirty sprue, and on the days when it rains, more dirt sticks to the castings. We are now planning to clean all of our sprue before it goes into the cupola, and add a given amount of sand and limestone in order to control the slag closer. It will be possible then to maintain a closer control of the iron oxide content in the cupola slag. Also, the iron oxide content of the cupola slag is higher during the months of April to October, due to the fact that the moisture content of the air is higher; and when the moisture content of the blast going into the cupola runs from 8 to 10 grains per cubic ft., you can readily see that the metal will be more highly oxidized. Therefore, the cupola slag will possibly contain more iron oxide than it would during the winter when the moisture content of the blast is around 1 to 3 grains per cubic ft. There is another variable that does change the iron oxide content of your cupola slag.

We have known for years that rusty steel charged to the cupola will produce tears, checks, and cracks in castings more readily than if you charge clean material. We use a duplexing process, where the iron is melted in the cupola and super-heated in the electric furnace, and it is more important to add clean steel to the electric furnace just before the iron is tapped than to add it to the cupola, due to the fact that any rust that adheres to the steel as it is added to the molten iron has not an opportunity to free itself. We maintain a very clean bath on the electric furnace iron, compared to the people that make cupola air furnace iron. They usually maintain a slag on the air furnace, but in the case of the electric furnace, we have none.

Therefore, we have to control our slag in the cupola rather than the air furnace. In listening to Mr. Schumacher's talk, I was wondering whether it would not be better to control the slag in the cupola to start with, than to control the slag in the air furnace. After all, if you can maintain the proper slag in your cupola, the slag in the air furnace should take care of itself.

MR. SCHUMACHER: That is true, Mr. Joseph. We try to maintain as much control of the slag in our cupola as possible. I believe you hit upon the point of difficulty, that there is a tremendous amount of in-

clusion in the iron, plus the slag produced right in the holding furnace itself.

I was trying to bring about a discussion of steel and melting stocks. I was trying to get hold of a good, No. 1, hand-picked steel, which was hard to get in our particular location, prior to the time that we went to bundled steel. Now we are using bright bundled steel, and this No. 1 stock, that we had been using prior to this time, was terrible. Junk dealers from whom the stocks were purchased, felt that they could unload most anything. We had a tremendous amount of inclusion from those particular stocks, and because the iron, having such a high iron oxide content, was sluggish, we turned on the fire pretty strong. I think that we suffered in our slag-manufacturing process, that is, we increased it owing to the fact that we fired so hard that we destroyed our melting and holding furnace, and produced slag. That is just one reason why we went to controlling in the furnace. The other reason is that after we shut the cupolas down, we wanted to eliminate as much of the additions of silica and ferromanganese and petroleum coke as we possibly could, because that is what I call up-and-down metal and we wanted to maintain the straight-line composition, and by maintaining a good slag, we are able to do that.

J. H. LANSING[2]: There is one thing which is not necessarily an inconsistency but needs clarification. In the conclusions there is the statement, "The author believes that the elimination of materials high in iron oxide content is the preventative means of producing a metal which will not misrun and hot tear easily." Thus, the only reference in the conclusion to eliminating hot tears and misruns is by the use of particular materials, there being no reference to slag control as the means. I thought you might want to make an addition or correction as in the abstract on the front of the paper, there is a statement, "He points out, from a practical standpoint, that it has been his observation that proper slag manipulation has facilitated the control of carbon, silicon and manganese, reduced refractory costs and has produced a metal which does not misrun and hot tear easily." In short, the abstract refers to the slag control as being the reason for crack eliminations and the conclusion refers to the charge materials as the reason. I know that you have in mind that both are reasons, but you will probably want to bring that out in the conclusion.

One other point is that possibly you, or Mr. Joseph, or both, may have developed a pattern which will crack when you have high oxide contact, and will not crack when you have low. If you have, that is a fine thing. I think that others will be glad to have it, too, and to use it to good advantage. I wonder if you would care to say whether you have such a pattern, or perhaps Mr. Joseph will say whether he has such a pattern.

MR. SCHUMACHER: We have. That is, we have a pattern wherein the

[2]Engineer, Malleable Founders' Society, Cleveland, O.

metal is poured at certain prescribed periods, and thereby associate our oxide content, our chemical composition and flowability, and everything, right at the same time, and it gives us a method of checking up on our operations.

We have tried patterns furnished us by other manufacturers and we have not obtained the results that we anticipated. I think that is one of the reasons for this whole thing, to see if we cannot bring out a more intimate control by means of such technical devices.

MR. LANSING: But your pattern will definitely show hot tears when you have high oxides, and you do not have any at all when you have low oxides. Is that a fact?

MR. SCHUMACHER: I could not say that the status of our efforts is conclusive enough to prove that.

MR. LANSING: Would Mr. Joseph discuss that point?

MR. JOSEPH: We do not have anything like that. We have castings that have crack strips on them, and by taking those off, naturally they will crack more easily, so that if you want to run any tests, take the crack strips off and the chances are that they will crack if the iron is not right. If the iron is right, they may not crack.

In the manufacture of steel, the steel maker deoxidizes his molten iron by adding aluminum, silicon, manganese, or various other elements. We have talked over deoxidizing our metal and have tried aluminum and silicon additions. We also have tried manganese additions and various other elements, and the metal that we use will graphitize the iron, except in the case of manganese. Manganese does not seem to graphitize the iron if you use a pure ferromanganese, low in carbon. If you use the 6 per cent carbon ferromanganese, that is apt to mottle.

We have not been able to eliminate the cracking tendency of a highly oxidized iron by adding a graphitizer or a deoxidizer to the molten iron. Possibly in our process, where the iron is melted and goes through the electric furnace so rapidly, it does not give the deoxidizer a chance to work. Maybe if you added the deoxidizer to the air furnace heat, and allowed the iron to rest there for 30 or 20 min., there is a possibility that a deoxidizer, added in the form of some ferro alloy, would have a tendency to reduce the oxide content of the metal.

That would have nothing to do, of course, with the slag, except that when the oxide content of the slag is high, usually the oxide content of the metal is high. But if it would be possible to deoxidize the metal bath, you should obtain results very much like the steel man does when he deoxidizes his metal.

Mr. Schumacher, have you tried any deoxidizer?

MR. SCHUMACHER: We have, Mr. Joseph, and found that our results concur more or less with what you have found. I do not know that our efforts along that line can approach what you have done, be-

cause having discussed with you previously some of the efforts that you have put forward, I can say that our efforts have been in the same direction. I do not believe that the deoxidizers have gotten us the results any more than they did for you.

The primary graphitization cut in too quickly. We just dispensed with oxidizers because there is no use fooling with that when, in my estimation, you have a big production schedule ahead of you. So we have leaned backward from trying to use the deoxidizers for that purpose.

MILTON TILLEY[3]: After operating for several years, we were beginning to think that high oxide in the charge affects hot tears deleteriously. Recently, I have tried aluminum deoxidation that you are talking about, and in that particular pattern, I did one thing I have never been able to do before, and that is stop the hot tears entirely, but I think it is a matter of graphitization. It seems to me that you have a particularly bad thing to control at the end of your heat. You have a serious problem to control that slag. I would like to see other people try this hot tear pattern business and see what they find out, see if it checks our results.

Talking about charging the cupola and oxidation, I do not know how to evaluate the difference between putting oxidation into the charge, and oxidizing after it is in there. It seems to me that you produce the same results by charging a light charge and oxidizing while melting, as by adding the oxides with the charge. I have never thought it a good practice to put in a light charge. We have made a few stabs at controlling slag in the furnace, but we have never got very far. Our oxide content seems to be so near to what we want it to be, around 10 per cent, remembering that you can get too low an oxide, too, that we have tried very seriously to change that condition.

W. R. BEAN[4]: The subject covered by Mr. Schumacher's paper is one of the most interesting that we have in the malleable industry today —when duplexing is practiced to the extent of almost 30 per cent of production capacity. The discussion is very timely.

My first statement will be to raise a question as to whether you can couple misruns, cracks, and hot tears, as being affected by the same group of conditions. The hot tear, it has seemed to me, comes not from the same causes as the crack in the casting, but from directly opposite causes. The hot tear is dendritic, therefore, it could be affected by tendencies to graphitize, as against tendencies to crack due to extreme hardness of the white iron. In some metals, not necessarily malleable, I am sure that that is the case, and I would like to raise the question without stating it as a fact that the two things come from directly opposite conditions. A metal that has the tendency to open up in solidifi-

[3]Metallurgist, National Malleable & Steel Castings Co., Cleveland, O.
[4]Vice President, Equipment Div., Whiting Corp., Harvey, Ill.

cation, due to selective freezing, seems to me to be the metal that produces hot tears.

Oxides are a factor in other ways, beyond any question, but the difficulty which there has been in measuring the content of oxides in the metal as cast, has seemed to make definite conclusions rather difficult.

Mr. Tilley has pointed out one feature of the operation that is described by Mr. Schumacher which appealed to me as being one of his principal problems. This is the four-hour lag between the bottom drop and getting out, what we call, the residue metal, the bath that has been built up and which it is necessary to build up for the purpose of having the metal in the furnace a sufficient length of time to do the two very vital things in duplexing. One of these things is to take metal, feeding into the furnace at 2600 to 2650°F. at the rear bridge wall continuously, and tap metal at a location roughly 20 to 25, or in some cases, 30 ft. distant at a temperature of 2900°F. or more. The other is to have a uniform analysis and uniform structure as taken from the furnace.

I was not one to accept cupola and air furnace duplexing in the early period as a means of making quality malleable iron, but today I know that malleable iron as good as any produced, is being made regularly by the duplexing process.

Metal goes in from the cupola at 2600 or 2650°F. and is tapped generally around 2900°F. Much of it is tapped at 2900°F. and frequently slightly higher. The flow of metal through the furnace is the factor which converts 2600°F. metal to 2900°F., which converts a 2.80 per cent to 2.90 per cent carbon metal as delivered by the cupola to 2.40 per cent to 2.50 per cent lower, in some cases, as tapped from the furnace.

The bath area time factor is vital in determining the amount of carbon reduction in duplexing. We advocate approximately 2 hours for the flow of the metal through the furnace. A bath volume which is approximately twice the hourly melting rate of the cupola is desirable. For example, 10 tons per hour, 20 tons in the furnace, will produce the results that are essential. There is no question but that the character of melting stock is important, and it is not alone the rust, the oxide that comes from rust, that is on the scrap, but as Mr. Tilley pointed out, the question of what happens to thin, light sectioned, steel scrap charged loose into a cupola, passing down through the preheating zone and the melting zone, subject to the atmosphere conditions which result from blasting of cupolas, some at very high pressure, and generally speaking, an excess of air is used in duplexing cupolas. This excess is used for two reasons. One is that it is necessary to get a somewhat lower carbon than a cupola normally delivers. The other is that it is desirable to run as low a sulphur content as is practicable, both in order to avoid the nuisance and the expense of desulphurizing. Therefore, for cupola and air furnace duplexing, that type of operation is more or less

essential. We do not care for high temperature from the cupola because there is time enough, and the ability to superheat in the air furnace the metal from the cupola to the temperature that is necessary, and the use of a small amount of coke, naturally results in lower temperature and lower carbon and lower sulphur. Of course, in some of the larger air furnace jobs, it is not as practicable to run the 9, 10 and sometimes 11 to 1 ratios that are run on some of the smaller duplexing jobs.

One thing that few of us take into account in cupola operation, with high steel charges, is the amount of coke that goes into the charging door as coke, and comes out of the tap hole as metal, which performs no function in the melting operation from the standpoint of heating the metal, consumes no air, and should be deducted, amounting roughly from 20 to 35 lb. of coke per ton of charge, which is used in carbonizing. This means that instead of the 9, 10, or 11 to 1 ratios, we are running for melting alone, ratios of 12 to 13 to 1, because the coke that comes out the spout as carbon has not burned, has not imparted any heat to the metal, and has not consumed any air.

The question of slags has not been given a lot of consideration up to the present time, and undoubtedly does deserve more consideration.

I would like to say that in duplexing, as it is practiced with the cupola and air furnace today, there are two sets of firing conditions. One set of conditions is with the jobs that have been converted from the bin-feeder system of coal pulverization and feed, the bin feed or direct melting, to duplexing with that same equipment, and the other condition comes where the direct-firing unit is used. The control of operations, both as to coal feed supply, the quantity of coal, and condition of flame, are definitely better with the direct-firing unit than with the bin-feeding unit. There is a facility in the direct firing for increasing the coarseness of the coal after the heat is up and the time comes to dampen the fire to hold the residue metal and to hold the analysis. That is a factor which, if understood, may allow those using the bin-feeder to help themselves somewhat to get a better control.

I have seen analysis figures in duplexing where the total range over 8 hours, between the high and low, including the last end samples in carbon, was 10 to 11 points for the day, and silicon, a variation through the period, somewhat lower, I think 7 to 9 points difference.

I would myself rather attempt to meet an exacting analysis specification on a given melt, we will say 100 tons per day, from a duplexing installation, than from direct fired furnaces melting that same amount of tonnage in separate heats. I am sure that it is possible to get a closer control of composition with duplexing under the best conditions than it is from the air furnace by direct melting.

W. H. DOERFNER[5]: We from the management side of business have

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put a problem upon our metallurgists and our melters that is rather insuperable. We buy a piece of equipment, usually as small as possible, and then after we get it into use, we start driving it very rapidly, trying to push as many tons through it as possible.

In our plant, we are doing one thing which I hope to be able to put on a real large-scale test. We are adding another series of cupolas and an electric furnace, and it is my hope that we will be able to run a dual foundry setup, under one roof, and then have one cupola and one electric furnace operating with thin scrap, or with high silicons, and having the direct comparison under one roof. I think that probably after we get this in, we will be able to present some ideas of how to control the thing a little better than we have up to date.

The metallurgist, or the melter, who has just one system in his plant has very, very little opportunity of making very much progress on this thing, because from time to time, his materials change, and he cannot correlate cause and effect.

W. R. JAESCHKE[6]: There has been a lot mentioned here with reference to slag control, except the influence that this slag might have on the possible carbon reduction in the furnace. I would like to ask Mr. Schumacher how long he leaves that slag in the furnace, or how heavy a blanket he permits to collect there, and what influence the slag has on the carbon reduction in the furnace.

MR. SCHUMACHER: We do not get our effect very rapidly on the carbon. As that slag deteriorates, our first noticeable effect is on the silicon or the manganese. As the slag, as we term it, gets highly oxidized, you will come to a point where the manganese will drop out very rapidly. The first effect that we have is on both silicon and manganese. We have not had the effect on the carbon.

There is one portion of this proposition of slag analysis that needs to be taken into account, and that is the analysis of your slag needs to include an SiO_2 analysis, and needs to include the FeO analysis, and believe it or not, I have seen records where there was an appreciable Al_2O_3 alumina analysis, found in slag. Where it came from, I do not know. I believe that the high iron oxide content, and possibly an accompanying high alumina content, is a contribution to the heavy fixed slag, and I do not like to maintain a heavy fixed slag. That we break up by simple limestone additions and keep the slag thin. If it gets to a point where it is so heavy that we are experiencing difficulty in holding temperature, we break it up with our limestone addition and get that portion out.

MR. JAESCHKE: It has been my experience, and the experience of other operators, that a heavy slag blanket, or any appreciable slag blanket, on the duplexing air furnace retards the carbon reduction, but it might be that by keeping this slag active with periodical limestone additions, that effect is not so noticeable. Yet, if Mr. Schumacher

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were trying to make a 2.40 per cent carbon iron instead of a 2.60 per cent, I was just wondering whether he could maintain that slag blanket and still obtain his necessary carbon reduction.

I think some operators have tried it, by some accident when they were down to low periods of production where the bath was not high enough to permit skimming the furnace. From the fact that they could not skim, they found that they did not lose any carbon at all, and they finished up with just as high carbon as came out of the cupola, due to the fact that the slag remained on the bath, but it was not this heavy slag, or slag activated by limestone, as practiced by Mr. Schumacher.

DR. H. A. SCHWARTZ[7]: It seems to me that we very greatly, oversimplify what we are talking about. There are a whole group of questions asked by various operating people of Mr. Schumacher, "When you do this, does this happen," and so on, and he can reply to that in so far as the questions can be translated in the light of everything else that is his practice, too.

The "everything else" is not going to have a parallel in any other shop. For a very great length of time, I have noticed that the tendency of everybody who talks from shop experience is to say, "After I did this, that thing happened; therefore, this thing is the cause of that thing." About 75 per cent of the time, this is misleading. There were some additional things that happened in the meanwhile to influence the result.

People have been running duplex operations with a desire to increase castings output per sq. ft. of foundry space. At the same time, they want to do something about the annealing to keep up with that increased output. The man running the duplexing has to make good iron and iron that will anneal 50 per cent faster than before. After a while, the plant manages to get some sort of balance with their particular operations, with their particular charge, their particular flame compositions, their particular slag compositions, the amount of pig iron versus steel in a charge, and dozens and hundreds of other things; their chemical analysis will produce white iron which will anneal in such a cycle as the management said it had to anneal in, and it is quite surprising how the mangement does not respect the laws of nature sometimes, when it says that it has to anneal. Then you begin to whittle down at one end of the annealing cycle, and you go to the melting and do something to make it possible to whittle down the annealing cycle. After a while, maybe the quality is not quite what it was, and the customer kicks, and you back up a little and fix that. By trial and error, over as long as the duplex operation has now run, a balance is established which produces the result, or as nearly the result as to quality and volume of production that management requires, within the limits of the equipment that stands before the metallurgist to work with.

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Then the war comes along, and somebody wants still more iron, or the Office of Production Management decides that you are not going to buy any 16 per cent ferrosilicon, if that happens to be what you want to use. Or you cannot have any nickel or aluminum, or you have to do any one of multitudes of things, which again upsets you and you have to start all over again.

The fathers of the industry had many years during which, under less difficult circumstances, they acquired a working balance. Their successors, working with better equipment and vastly more knowledge, have acquired a working balance much sooner, but that balance is still just as easily overset as it ever was.

The practical problem of slag analysis, I think, is infinitely more complex than the malleable foundry man has ever admitted it to be. It was too complex for the open-hearth steel melter until Charles Herty started directing attention into the right directions. I do not think it means such a terrible lot—with deference to Mr. Schumacher—what a slag composition is, just in the abstract. On a paper there is written an analysis of slag. I am not so sure it tells you anything because everything depends on how long the slag was in contact with the iron, what opportunities there were to reach equilibrium. It is never completely reached. Did it come anywhere near being reached or did the metal just flow by underneath the slag, and you would get this slag and this iron without pretense of equilibrium. In one man's operation, he will approach an equilibrium to a great degree, and in another man's operation, the man who perhaps holds his iron longer, one may come closer.

Even the steel melter has not been able to show that for so much ferrous oxide in the slag, even if the rest of the things do not vary so very much, there is so much oxygen in the steel. That condition is approached to some extent, but it is not accurately reached.

You have another proposition. Suppose you develop ferrous oxide. It meets a very vast amount of carbon. If you apply Herty's equilibrium number, there is recognized in steel melting a product of oxygen and carbon which is the equilibrium value of the product. That would mean almost no oxygen at all with the amount of carbon that exists in a bath of molten white iron, yet you have more oxygen than required. Why have you more oxygen? Because you have dissolved ferrous oxide in the slag, perhaps as fast as it formed under the flame, so fast that the reaction within the molten bath, which is dependent on the time that it takes for an atom of oxygen and an atom of carbon to meet each other, has not kept up with the absorption of oxygen. It is an actual fact that while you are removing carbon from a bath in the air furnace stage of the duplexing, you are not adding oxygen but removing oxygen. Part of that removal is by the mechanism of combining carbon with oxygen that was in the iron and which is partially being taken out as carbon monoxide. I do not know the facts well enough to know whether any oxygen is coming from the combustion gases above, down, or not, but certainly part of it is being eliminated. The oxygen

content of at least our duplex malleable is higher when it goes into the air furnace than when it comes out of the air furnace. One answer to that is that it is safer to argue from oxygen determinations in the iron than from ferrous oxide determination in the slag. I am not prepared to defend this statement, but it is pretty generally accepted that the addition of a considerable excess of aluminum to liquid ferrous alloys will combine all of the oxygen to Al_2O_3 in fractions of a second. The people in the steel business seem quite content with that and I am just taking it on faith that the pioneers knew what they were talking about. This permits an oxygen determination by analyzing for the resultant alumina. Even if you start with the very simple proposition "How much oxygen is in the iron when the slag has this-and-that composition," you have a couple of Ph.D. theses ahead of you before you step along further in that reaction. The analyses are quoted only in terms of ferrous oxide. It makes a lot of difference what is in there and what is put in. Suppose you make ferrous silicates out of the FeO, the resulting slag is inactive although it contains FeO by analysis. If you add calcium oxide, the first thing it tries to do is to replace iron oxide in the silicate, and you arrive at what is a silicate of calcium in which there is dissolved an oxide of iron, plus an oxide of manganese, and if you examine that slag either microscopically or by x-ray means, you find there are two distinct phases, one has the crytallography of the silicates, the other of the oxides and the slag is more active. You put in more lime. You get to the place where the lime has coated itself with a refractory silicate. It swims around there and is not chemically part of the slag.

After a while, iron oxide will eat that encrusting shell off, and you will get the slag actually containing the calcium, containing it in liquid solution and not as a piece of entirely separate substance. We have had to follow that with experiments quite expensively—I said expensively, deliberately. You can add enough lime so that you can make some of your iron oxide into a dicalcium-ferrite. That Fe_2O_3, though it contains more oxygen than FeO, will not react with the carbon of the steel. The reason it will not react is because neither the dicalcium-ferrite nor its Fe_2O_3 will dissolve in the metal. You get only a reaction between the slag and the metal, whereas the ferrous oxide is fairly soluble and it goes down and reacts in the metal, and you get a boiling result.

I apologize for departing so far from the subject, but I should like to point out that you must not consider these things only by saying, "If I change from bundled scrap to some other kind of scrap," "If I change from ABC coke to Indianapolis coke," or "If I change from this to that."

What that means is not just one simple question, but the question is, what does that mean in view of all of the other conditions upon which your practice has been built up?

MR. BEAN: Dr. Schwartz mentioned the removal of carbon. Mr. Joseph mentioned the moisture content of air. Carbon is removed from metal by the action of hydrogen, and not alone by the action of oxygen.

Hydrogen is, under certain conditions, very active in removing carbon from malleable iron in a molten bath.

We kept a complete record of several thousands of air furnace heats, running 12 to 15 furnaces steadily at that time, and through the winter months, the carbon lost in melting was appreciably less than through the summer months. The actual difference between the high month of the year, which proved to be August, and the low month of the year, which was February, was of the order of 25 per cent of difference between the amount of carbon removed over the entire month of February, and the amount of carbon removed during the month of August. That is just one more variable that we have to contend with in the production of iron, melted with fuel and the air.

This condition was brought to my attention through the fact that as spring approached, we had to increase the amount of pig iron required in an air furnace charge in order to maintain a constant carbon in the metal. We increased the pig iron content of the charge in the spring and decreased this in the fall. This became regular routine in air furnace operation.

Dr. Schwartz and I discussed this many times, and he would not agree with me until all of the furnace operation in the plant was on pulverized coal, and the human element of the lazy furnace fireman in hot weather was out of the picture.

DR. SCHWARTZ: First I disagreed with Mr. Bean, then I agreed with him, and now I again disagree with him. I want to point out the cause of the disagreement, though I think the facts happened exactly as Mr. Bean mentioned them. I object to the mechanism now, that any methane or any other hydrocarbon is formed. I offer the following explanation: I think it is provable by analysis that wet-weather iron contains more hydrogen than dry-weather iron. At the time when you put steam from the moisture in the blast into the furnace atmosphere, the steam dissociates into the atomic hydrogen and oxygen. The atomic hydrogen dissolves faster than the molecular, giving you a faster reaction. The rest goes up the flue. Atomic oxygen dissolves easily and reacts with carbon.

MR. BEAN: In this period from which the quoted record was obtained, we analyzed and kept the record for silicon, as well as carbon, and the silicon was practically constant throughout the year, taking the records month by month, and that led me to believe that it was the effect of hydrogen rather than oxygen.

Dr. Schwartz may be right. The fact remains that there is a definite and substantial difference in air furnace metal during different periods in relation to the humidity content or water content of the air used in combustion. Figuring just roughly on a 20-ton heat; we put through in the dry month about 500 lb. of water, and in the month of highest humidity, it ran up to about 3000 lb. This went through the grates of a hand-fired furnace into the melting chamber and over the bath.

American Synthetic Sand Practice†

By Norman J. Dunbeck*, Eifort, Ohio

Abstract

The author defines the term "synthetic sand" as any sand which is made in the foundry, as required, from materials selected and proportioned by the foundryman to best fit his particular needs. He then discusses some of the terms used in connection with synthetic sand practice in American foundries and then turns his attention to the selection of materials for such sands. He discusses such points as the base sand used and the properties that it should possess; various types of clay bonds which he divides into three classes, kaolinite, illite, and montmorillonite, showing a table of the relative values of these three types of clays under twelve classifications. The various clay classes, their properties and applications are then discussed specifically. The author then brings out the value of combinations of clays to confer specially desired properties on sands, illustrating particularly the value of such combinations in the matter of hot strength. He also outlines what he considers the best clays or combinations to be used in synthetic sands for light, medium and heavy non-ferrous, gray iron, malleable and steel castings. In discussing the methods of application of clays, he calls attention to the proper methods of adding various types of clays in sand heaps, system sands and facing sands. He comments briefly on sand reclamation and at some length on some of the points which must be taken into consideration in testing and control work. The author concludes his paper with an outline of the disadvantages of both naturally-bonded and synthetic sands and the advantages of synthetic over naturally-bonded sands.

Definition of Synthetic Molding Sand

1. When metal is cast against molding sand, the clay con-

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† Official Exchange Paper of the American Foundrymen's Association to Institute of British Foundrymen.

tained in the sand close to the casting is dehydrated and it loses strength. It is further weakened by normal accretions of burned core sand. This weakened sand often is discarded, although it may be as good in refractory value and grain structure as when it was new. This is costly and inefficient. Many foundries now add bonding clays to restore strength, and in this way, effect elimination of new bonded sand or a considerable reduction in the amount used.

2. Bonding clays are strong, plastic clays which develop strength rapidly, even when used in small amounts. They may be added to new or burned silica sand to form synthetic sand. Some sand producers now manufacture what is called synthetic sand by the addition of bonding clay to unbonded or low bonded sand at the sand pits. As generally used in American foundry practice, however, the term synthetic sand covers any sand which is made in the foundry, as required, from materials selected and proportioned by the foundryman to best fit his particular needs. A rebonded sand is one whose usefulness or life is prolonged by the addition of bonding clay.

3. A certain amount of burned sand is lost from the foundry each day on the castings. Common practice in making the synthetic sand is to add enough clay bond to the used sand to restore strength and enough silica sand to keep up volume. Since this added silica sand and the core sand used, are the only new materials entering the sand, with the exception of the bonding clay, they will eventually compose the entire heap or system. It is, therefore, essential to select a silica sand to be added which has a grain size that will give the finish and permeability required.

4. Synthetic sand has been used in steel foundry practice for many years. Its use is so common that steel foundrymen do not often speak of their mixtures as synthetic sands. The term, of course, describes such sand, but probably is used more often by iron foundrymen in describing their combinations of bond clay and sands.

5. The general procedure followed in cleaning, classifying and rebonding used sands is termed sand reclamation. The term "clay bond" is a general one and may refer to fire clay bonds, other plastic clays, bentonites or bentonitic clays.

6. The reclamation and rebonding of used iron foundry sands

reached substantial volume in the United States between 1925 and 1930 and has increased steadily since that time. It now seems probable that a larger tonnage of castings is made annually in synthetic sand than is made in naturally bonded sands.

7. Some objection has been raised to the term "synthetic sand" because the word "synthetic" might imply that the material was a cheaper and inferior substitute for naturally bonded sands. It has been suggested that the sand be called "artificial sand" or "manufactured sand." The term "synthetic" has been in use so long that it will probably be continued. However, it is worth noting that the product is used because the user believes it to be superior as well as cheaper than the natural product.

8. The writer also has read occasional references in the British technical press to the fact that synthetic sands are widely used in the United States because there is a scarcity of good naturally bonded sands. There are deposits of high quality naturally bonded sands in almost all parts of the United States and they occur in enormous tonnages.

SELECTION OF MATERIALS

Base Sand

9. A synthetic sand may be made from all new unbonded sand and clay, from naturally bonded sand and clay, from used molding or core sand and clay, or from combinations of these various materials. When it is proposed to rebond certain sand heaps, it should be realized that there is a certain loss of sand on the castings of which only a portion is recovered. This loss must be replaced by daily additions of sand which may be any of the above materials. The original sand in the heap eventually will be replaced entirely by the sand in the daily addition, resulting in a final mixture composed of the base material and bond. Therefore, the final result is the same, whether we start with a completely new synthetic mix or whether we rebond old sand.

10. Our base sand may be a bonded sand, a low bonded sand or an unbonded sand. An unbonded sand is preferable since the clay in naturally bonded sands is not usually efficient nor refractory. The so-called bond in natural sands also frequently contains a substantial per cent of silt which adds little to strength, increases the amount of tempering water required and reduces permeability

and flowability. Some low-bonded sands are desirable since the small amount of natural clay present provides a priming surface on the grains and substantially reduces the amount of bonding clay which must be added. Final decision on base sand depends upon the delivered cost, a cheap, local, low-bonded sand being preferable to a costly, distant, unbonded sand.

11. The base sand is examined for these four properties:

(1) Grain size, shape and distribution.

(2) Minimum clay content.

(3) Maximum refractory value.

(4) Minimum expansion.

12. The reasons that we wish minimum clay content, minimum expansion and maximum refractory values are apparent. Some thought must be given to grain size, shape and distribution. While the type of bond clay used will have effect upon flowability, and hence finish, it is decidedly true that fine finish is obtained only from fine grained sands. While the type of clay will affect the permeability, it is still true that very high permeabilities are given only by comparatively coarse sands. Therefore, we must seek the proper grain size for our work. In the search for such sand, we also consider grain shape and distribution.

13. For some years, a perfectly round grain was considered the ideal. It now is realized that such round grains require a comparatively higher amount of bonding material and cause greater difficulty from cutting and scabbing than do sub-angular grains, which are preferable. It also has been found that many sub-angular grained sands give satisfactory permeability, and may even give higher permeability, than some round grained sands, despite all theories to the contrary. Burned core sand from oil-sand cores is an excellent material to rebond as the grains have a rough surface and accept bond readily.

14. It was once thought that all fines should be eliminated and our sand grains concentrated upon as few screens as possible. It now is known that a certain percentage of fines is desirable and that too heavy a concentration of grain on a few screens may give a sand having a pronounced tendency to rat tail or buckle.

15. This is due to the close packing of uniform grains in a sand of high flowability. When the silica grains expand, they break

the mold face. A minor break causes a rat tail, a larger break causes a buckle and a still larger break causes a scab, although it is recognized that scabs also are caused by other reasons. In the last case, the moving metal penetrates under the broken surface or removes a portion of the sand replacing it with metal. These defects appear in maximum development in the cope of the mold.

16. The fines in sand have much higher expansion than the coarser grains, yet their addition to the coarser grains reduces expansion difficulties. It has been said that the fines provide a cushion between the larger grains, but the writer believes that their corrective action is due to the simple fact that they reduce flowability, thus increasing the distance between the coarser grains in the rammed mold face. This seems corroborated by the fact that a very small addition of corn flour is our best known method of stopping these cope defects, outside of changes in the sand grain distribution, and corn flour reduces flowability faster than any other common molding material.

17. Present trend is to seek the bulk of the material on three adjacent screens with a few per cent on possibly two more adjacent screens. Such a sand still gives high permeability in relation to its fineness but the distribution is such as to reduce expansion difficulties. Some American foundries, which use large quantities of oil-sand cores, shake out as much as possible of the burned core sand into the sand systems and also return to the systems burned core sand which is carried away with the castings. It is then possible for them to effectively control the fineness of the system sand by varying the proportion of fine and coarse sand in their cores. This has been described more fully by Zirzow* and his paper is probably available in many English libraries in the bound volumes of the A.F.A. *Transactions.*

18. In any molding sand, we are interested principally in (1) grain size, (2) green strength, (3) dry strength, (4) hot strength, (5) permeability, (6) durability, (7) flowability, (8) moisture required, (9) resilience, (10) expansion, (11) contraction and (12) sintering point. In selecting a naturally bonded sand, we have the difficult problem of finding as many of these twelve properties as well developed as possible within an economical radius of location. In compounding a synthetic sand, we must find only

* Zirzow, E. C., *"Sand Control in a Malleable Foundry,"* TRANSACTIONS, American Foundrymen's Association, vol. 45, pp 134-156 (1937).

three properties as we wish them in base sands, namely: grain size, permeability and expansion. The other nine properties can be controlled to a substantial extent by the selection of clay bond to be used. Since there are many types of clays available, the problem of making a synthetic sand is considerably simpler than the problem of finding an equally satisfactory naturally-bonded sand.

Bond Clay

19. Almost any kind of plastic clay will develop some bonding strength. Special clays are used because the clay should not only give green strength but must also develop dry strength, have a high sintering point, the ability to mix rapidly, good durability, adequate strength at high temperatures, moderate contraction at high temperatures and other special requirements for specific problems.

20. The selection of the proper clay requires a knowledge of the essential properties of the general groups of clays. Until a few years ago, there was considerable mystery, even among clay producers themselves, as to the reason for different results given by different clays. Recent work indicates that the mineral composition of clay is the most important single factor in determining results. Thus, two clays, each having the same percentage of clay substance, might deliver approximately the same strength if kaolinite was the principal mineral in the clay substance of each clay. Two other clays, each having the same percentage of clay substance, might differ very sharply in bonding value if kaolinite was the principal mineral in one while the second was a mixture of kaolinite and illite (beidellite). In addition, the strength of a clay bond is affected by the percentage of clay substance and the type ion adsorbed on the surface of the clay particles. The importance of the adsorbed ion is clearly indicated by Western and Southern bentonites. These materials, which differ radically in physical properties, are practically identical in particle size and mineral composition, but the Western bentonite carries basic adsorbed ions while the Southern carries acid adsorbed irons.

21. The high quality clays in each group can be expected to give generally similar results but there is, of course, a wide range in quality between the best and worst clays in each group. If we eliminate refractory clays of low bonding power, the presently available American bonding clays may be grouped into three

classes determined by their dominant mineral. These classes are given in Table 1 together with their relative values for various properties in the production of synthetic sand. Comparison merely indicates the order from best to worst in each property.

Table 1

RELATIVE VALUE OF VARIOUS TYPES OF CLAYS

	Kaolinite	*Illite*	*Montmorillonite*	
			Southern	*Western*
Highest Green Compression Strength.....	4	3	1	2
Highest Dry Compression Strength.....	2	3	4	1
Highest Permeability	4	3	1	2
Least Tempering Water Required.....	4	3	1	2
Highest Sintering Point.....	1	4	2	3
Greatest Durability.....	1	3	4	2
Highest Flowability.....	3	2	1	4
Best Collapsibility.....	3	2	1	4
Highest Resilience.....	2	3	4	1
Least Contraction @ 2500°F.....	1	4	2	3
Fewest Lumps in Shake Out Sand.....	3	2	1	4
Least Intensive Mixing Effort Required....	4	2	1	3

Kaolinite Clays

22. Practically all of the refractory bond clays, such as fire clay and ball clay, fall into this class and this is the most widely used type of bond clay in the United States. Fire clays of excellent plasticity and refractory value are available in the United States and, as a result, the more costly ball clays have not been able to justify entry into the market at their higher cost. The best of these fire clays have a fusion point of 3050-3100°F., a clay content according to A.F.A. methods (fineness 0.02 mm.) of about 95 per cent and a clay content according to the pipette and hydrometer methods (fineness .005 mm.) of about 75 per cent.

23. There is a greater difference in value between the good clays and poor clays of this class than between the class itself and any other class. *Any statements about these clays, or the clays in following classes, will refer to the best of the individual groups.*

24. A specially selected and prepared clay of this type is essential to good results. Since this type of clay is most refractory and gives the highest possible sintering point, it is particularly

well suited to heavy castings and the alloys which are melted at high temperatures.

25. More of this clay must be used for any given strength than of the high strength clays to be later described. Where very high permeability is required, it would, therefore, be preferable to use a higher strength clay. An exception to this would be the case of the foundry which could not secure cheaply a base sand of the exact fineness required. In such case, the greater volume of this type of clay which would be used would tend to smooth up the surface of a coarser sand, giving the finish required.

26. The kaolinite clays give moderate green strength, moderate dry strength, good flowability, highest sintering point and lowest contraction at high temperatures of any type of clay. They are also lowest in cost and have highest durability.

Illite Clays

27. Illite clays are not widely used in the United States, but they are included because many naturally-bonded sands have illite as a major constitutent of their clay content.

28. There is wide variation in the value of various illites, but the best clays in this group have a finer grain size than the kaolinite clays and develop somewhat higher green strength. It is necessary to use a lesser amount which results in higher permeability. They give good flowability and reasonably high sintering point. They have moderate dry strength and rather high contraction at high temperatures. They have low durability as compared to the kaolinite clays.

29. They may be considered as an intermediate clay with higher strength than the kaolinite clays, but much lower strength than the montmorillonite clays. Their use depends upon comparative delivered costs at any particular location.

Montmorillonite Clays

30. The montmorillonite clays used for bonding in the United States are the Western bentonites, produced principally in Wyoming, and the Southern bentonites, produced principally in Mississippi. Both types of clays are available and carried in stock in England.

31. These clays have the finest grain size of any bonding

clays. They develop double the green strength of the best kaolinites. The Western bentonites swell when placed in water while the Southern bentonites are non-swelling. The bentonites give the highest permeability of any clays and the highest or lowest dry and hot strengths depending upon the type selected.

Combinations of Clays

32. The most important recent American research work on sands has been on hot strengths and the most important recent development in practice has been the use of combinations of clays instead of a single clay.

33. Tables 2, 3, 4, 5 and 6 show hot strength behavior and will be discussed briefly since this information is important in choosing the single clay or the combination of clays to be used.

34. Table 2 shows a rather startling increase in hot strength with only slight increases in clay and water content. This indicates that kaolinite clays have adequate hot strength for any job when properly handled. It may also indicate the source of some cracked castings in the malleable industry, since an overtempered batch of sand has far higher hot strength than the same sand properly tempered.

35. Table 3 shows the gradual increase in hot strength from Southern bentonite, through combinations, to Western bentonite.

Table 2

EFFECT OF CHANGES IN QUANTITY OF A KAOLINITE CLAY AND WATER ON HOT STRENGTH

Base Sand — Unbonded Silica — Average Grain Fineness — 53 — *Bond or Combination*			
Per cent Bond	12	12	10
Moisture, per cent	4.0	3.5	3.3
Permeability	85	87	103
Green Compression, lb. per sq. in.	8.5	10.5	8.7
Green Deformation, in. per in.	0.019	0.017	0.015
Dry Compression, lb. per sq. in.	71.5	52.0	47.5
Hot Strength, lb. per sq. in.			
500°F.	55	52	38
1000°F.	100	85	60
1500°F.	153	87	80
2000°F.	550	400	295
2500°F.	5	6	5

Table 3

HOT STRENGTH OF COMBINATIONS OF BOND CLAYS

Base Sand — Unbonded Silica — Average Grain Fineness — 53 —

Bond or Combination†	*S.B.*	*S.B. 75% W.B. 25%*	*S.B. 50% W.B. 50%*	*S.B. 25% W.B. 75%*	*W.B.*
Per cent Bond	4	3.8	4.3	4.8	5
Moisture, per cent ...	2.6	2.5	2.5	2.5	2.5
Permeability	178	180	171	160	167
Green Compression, lb. per sq. in.	9.9	9.6	9.8	9.8	9.6
Green Deformation, in. per in.	0.008	0.012	0.012	0.011	0.012
Dry Compression, lb. per sq. in.	47.0	42.0	59.0	69.0	83.0
Hot Strength, lb. per sq. in.					
500°F.	21	31	38	43	75
1000°F.	35	42	53	55	74
1500°F.	30	70	160	175	195
2000°F.	25	65	90	95	490
2500°F.	3	4	5	4	8
*Strength After Cooling from 800°F.	20	37	40	45	55

* Retained strength after cooling from 800°F. indicates quantity of lumps to be expected in shake out sand.
† S.B. — Southern Bentonite, W.B. — Western Bentonite.

A foundry might have washes and cuts due to the low hot strength of Southern bentonite or difficult shake out, lumpy sand and cracked castings due to the high hot strength of Western bentonite. A combination of the two may be made to yield the exact strength required.

36. Table 4 shows the same progression from low to high hot strength when mixing Southern bentonite and a kaolinite clay. When difficulty is experienced with either low or high hot strength from a single bond, certainly it is only common sense to use a combination that will give the hot strength required to stop cutting and washing and no more. This extends sand control into a hitherto untouched and frequently troublesome field.

37. Table 5 shows that combinations of kaolinite clay and Western bentonite, instead of giving hot strengths intermediate to the bonds used, gave a peak strength more than twice as high as

either component. This could hardly have been predicted from low temperature dry strength testing. Such combinations should have excellent application for heavy iron or steel castings.

38. Table 6 shows that additions of cereal binder (corn flour), pitch and rosin sharply increase the dry strength of Southern bentonite, although the increase in hot strength is such as to still provide a highly collapsible sand. Such a sand should be desirable for steel castings which have a tendency to crack. It is interesting that the addition of cereal binder to Western bentonite did not appreciably increase dry strength but caused a sharp decrease in hot strength. This indicates that steel foundrymen who have used such combination for increased strength have not benefited much in that respect, but have actually provided a more collapsible sand.

Table 4

HOT STRENGTH OF COMBINATIONS OF BOND CLAYS

Base Sand — Unbonded Silica — Average Grain Fineness — 53 —

Bond or Combination†	*K*	*75% K 25% S.B.*	*50% K 50% S.B.*	*25% K 75% S.B.*	*S.B.*
Per cent Bond	12	9¼	6½	5	4
Moisture, per cent ...	4.0	3.7	3.2	2.6	2.6
Permeability	85	118	139	167	178
Green Compression, lb. per sq. in.	8.5	11.0	10.4	12.9	9.9
Green Deformation, in. per in.	0.019	0.015	0.015	0.012	0.008
Dry Compression, lb. per sq. in.	71.5	83.0	71.0	55.0	47.0
Hot Strength, lb. per sq. in.					
500°F.	55	54	35	40	21
1000°F.	100	59	50	48	35
1500°F.	153	100	62	30	30
2000°F.	550	450	238	85	25
2500°F.	5	5	5	4	3
Strength After Cooling from 800°F.	65	74	43	27	20

† K — Kaolinite Clay, S.B. — Southern Bentonite.

Table 5

HOT STRENGTH OF COMBINATIONS OF BOND CLAYS

Base Sand — Unbonded Silica — Average Grain Fineness — 53 —

Bond or Combination†	*W.B.*	*75% W.B. 25% K*	*50% W.B. 50% K*	*25% W.B. 75% K*	*K*
Per cent Bond	5	5.2	6.8	8.5	10
Moisture, per cent	2.5	2.3	2.8	3.5	3.3
Permeability	167	162	154	116	103
Green Compression, lb. per sq. in.	9.6	9.1	8.7	8.8	8.7
Green Deformation, in. per in.	0.012	0.013	0.017	0.018	0.015
Dry Compression, lb. per sq. in.	83.0	75.	125.	120.	47.5
Hot Strength, lb. per sq. in.					
500°F.	75	40	65	116	38
1000°F.	74	65	100	160	60
1500°F.	195	120	240	250	80
2000°F.	490	560	830	1000+	295
2500°F.	8	5	6	8	5
Strength After Cooling from 800°F.	55	61	89	110	

† W.B. — Western Bentonite. K — Kaolinite Clay.

CHOICE OF CLAY

39. From the results in various tables, we can choose certain clays for certain work.

Non-ferrous

1. Light — Southern bentonite for its combination of high permeability and high flowability.

2. Heavy — Fire clay for economy if permeability is not too important or to smooth up sand if only coarse sands are available. Western bentonite for highest permeability combined with high hot strength. Fire clay-Southern bentonite for high hot strength and economy if slightly lower permeability is acceptable.

Gray Iron

1. Light — Southern bentonite for its combination of high

permeability and high flowability.

2. Medium — Fire clay for economy if permeability is not too important or to smooth up sand if only coarse sands are available. Western bentonite for highest permeability combined with high hot strength. Fire clay-Southern bentonite for high hot strength and economy if slightly lower permeability is acceptable.

3. Heavy — Fire clay for high hot strength and economy particularly on dry sand work where permeability is not important. Western bentonite for highest permeability combined with high hot strength. Fire clay-Western bentonite for highest hot strength.

Malleable

1. Light — Southern bentonite for its combination of high permeability, high flowability and moderate hot strength.

2. Medium — Fire clay for economy. Southern bentonite

Table 6

HOT STRENGTH OF AUXILIARY BINDERS

Base Sand — Unbonded Silica — Average Grain Fineness — 53 —

Bond or Combination†	*S.B.*	*4% S.B. 1% C.F.*	*W.B.*	*5% W.B. 1% C.F.*	*4% S.B. 3% Pitch*	*4% S.B. 1% Rosin*
Per cent Bond	4		5			
Moisture, per cent	2.6	3.6	2.5	3.5	3.5	3.5
Permeability	178	138	167	152	110	128
Green Compression, lb. per sq. in. ...	9.9	8.2	9.6	9.3	11.7	8.1
Green Deformation, in. per in.	0.008	0.034	0.012	0.027	0.013	0.012
Dry Compression, lb. per sq. in ...	47.0	133.0	83.0	87.	158.	145.
Hot Strength, lb. per sq. in.						
500°F.	21	85	75	63	67	42
1000°F.	35	48	74	50	144	45
1500°F.	30	45	195	105	102	41
2000°F.	25	65	490	280	100	96
2500°F.	3	3	8	6	6	3

† S.B. — Southern Bentonite. C.F. — Corn Flour. W.B. — Western Bentonite.

for highest permeability and flowability combined with moderate hot strength to prevent cracked castings. Fire clay-Southern bentonite for moderate permeability and moderate hot strength. Western bentonite-Southern bentonite for highest permeability combined with moderate hot strength.

3. Heavy — Fire clay for high hot strength and economy particularly on dry sand work where permeability is not important. Western bentonite for highest permeability combined with high hot strength. Fire clay-Western bentonite for highest hot strength.

Steel

1. Light — Southern bentonite plus cereal binder for its combination of high permeability and high flowability.
2. Medium — Southern bentonite-Western bentonite plus cereal binder for high permeability, high dry strength and moderate hot strength.
3. Heavy — Fire clay plus cereal binder for high dry strength, high hot strength and high sintering point. Western bentonite plus cereal binder for high dry strength, high hot strength and highest permeability. Fire clay-Western bentonite plus cereal binder for high dry strength and highest hot strength.

METHODS OF APPLICATION

In Sand Heaps

40. Several methods may be used to add bonding clays to foundry sand. A small amount of clay bond may be placed on each mold before it is shaken out. With most bonds, this is satisfactory on heaps where a sand cutter is used for sand preparation only, if the cutting and mixing is done most thoroughly. It also may be spread over a heap and cut in, but full efficiency is not obtained from the bonding material in such usage and there is danger of clay balls forming. When this method is used, the clay and heap sand should be cut thoroughly dry before tempering water is added.

41. Fire clay and illite must be used in considerable quan-

tity when mixed by sand cutter instead of muller and there is a tendency for clay balls to form. Western bentonite mixes reluctantly because of its swelling nature on contact with water. Non-swelling Southern bentonite quickly slakes into a slurry on contact with water and is a safe material for this type of application. This has some importance in that it makes the advantages of synthetic sand available to foundries that have not felt they could use bond clay because they do not have intensive mixers.

42. Some foundries mix the clay bond with water to form a slurry and use this mixture as their tempering water. This gives high efficiency from the amount of clay so used, but it is not possible to get in enough clay for very high strengths by this method because of the relatively small amount of tempering water usually required. The method is economical since it eliminates transportation and mixing costs as compared to machine mixing. The strength delivered depends not only upon the strength of the clay used, but also upon the quantity which it is possible to carry in slurry form. This, in turn, depends upon the maximum viscosity of slurry which can be pumped. Such point of maximum viscosity for average conditions is given in Table 7.

Table 7

CLAY CONTENT AND RELATIVE STRENGTHS IN SLURRIES

	Per Cent Clay In Slurry	*Relative Effective Strength*
Western bentonite, per cent	8.25	100
Southern bentonite, per cent	34.20	491
Fire clay, per cent	52.30	288

43. Because Western bentonite immeditely swells to a gel, only a relatively small amount can be incorporated in a slurry of pumpable viscosity. Southern bentonite, being non-swelling, readily slakes in water in the same manner as does fire clay. The figures for relative effective strength are arrived at by using Western bentonite as a base at 100 per cent, and computing other strengths from known relative values and amounts present in slurry.

44. The best method of rebonding a heap of sand, where a muller mixer is available, is to manufacture a synthetic sand.

This may be a mixture, in any proportions, of used molding sand, burned core sand or new silica sand, with the proper amount of clay bond. Such a sand may be made with high or low permeability and with high or low strength, thus giving a very flexible control of sand conditions. Such a sand often is made by a night shift on the mixer, so as not to interfere with the daytime production of core sand or facing sand. When the proper sand has been prepared, it is added to heaps or systems exactly as is natural molding sand, thus avoiding any change in sand handling methods.

45. When there is sufficient or excess volume of sand in system or heap, a concentrated mixture of sand and clay bond may be made. This may vary from 20 to 40 per cent bond. Such mixtures must be mixed very dry, usually with 2 per cent of water or less. These mixtures reduce handling costs and aid in controlling volume of sand. Less efficiency is given by the amount of clay in such concentrated mixtures than is given when smaller amounts of clay are mulled thoroughly at their proper moisture content.

46. The statement is still sometimes made that the use of clay bond results in loading up a heap with clay which reduces permeability. This might be true if clay were added continuously to the same mass of sand. Actually, the sand is constantly changing. Each day a portion of it is carried away on the castings and an equal volume of prepared sand is added. A cycle is thus established where permeability is maintained at any desired point by varying the composition of the added sand.

47. Synthetic sand is so flexible that it makes sand control easier. The purpose of sand control is to permit prediction of results to be obtained through proper selection and testing of materials. If bad castings result, the fault is with the sand control and not with the sand, whether naturally bonded or synthetic.

In Sand Handling Systems

48. It is a simple matter to add clay bond to any sand handling system, if the system has any type of sand mixer. Any type of clay will work successfully because the clay is added in small regular additions. The clay may be placed on top of each mold before it reaches the shake out, it may be added manually or by any type of feeder at the shake out, it may be fed to the mixers as a slurry, or it may be fed into the system in any con-

venient manner as a prepared synthetic sand of any desired strength.

49. Burned core sand which is shaken out into the system sand usually aids in maintaining necessary volume of sand. If additional silica sand is required, either for volume or permeability, it may be added in any convenient manner.

In Facing Sands

50. Bonding clays are of particular value in preparing facing sands, since they permit great flexibility in the control of strength without the notable variation in permeability which would accompany similar changes in strength if effected by additions of naturally bonded sands. The usual facing mixture consists of used molding sand, plus some casting cleaning element, (such as sea coal for iron castings) plus clay bond, plus enough silica sand to give the required permeability. Burned core sand from oil-sand cores may replace the silica sand if its grain size is such as to ensure necessary permeability. Since such silica or core sand is the only new sand material entering the foundry, it eventually will dominate the heap or system sand which comes back to the mixer to be made into facing or synthetic sand. As the permeability of this returned sand rises, the amount of burned core sand or new silica sand being added to the facing mixture is decreased. In foundries where it is essential to produce a very fine finish, a fine silica sand is used. In any case, the objective is to secure a sand of maximum fineness which will give the permeability required through its uniformity.

51. When a durable clay is used in the facing, it loses only a moderate amount of strength on pouring and the remaining strength, upon mixture of facing and backing sand, is frequently sufficient to maintain the strength of the backing sand without further clay additions.

52. In many American iron foundries, some casting cleaning element, such as sea coal, is added to all the system sand as mixed, thus, in effect, making all the sand in the system into facing. This eliminates the cost of the separate mixing, storage and transportation of facing sand. No difficulty is experienced in the preparation and use of such sand except for the fact that the sand may become quite hot when reused several times per day. In such cases, it is essential to use a bond clay which does not become sticky when hot.

Sand Reclamation

53. Many foundries have now installed sand preparing and reclaiming units. Such units may have a floor level grating into which is dumped excess or used molding sand, burned core sand, gangway sweepings and, in general, any sand that can be collected around the foundry. A magnetic separator removes metal, a coarse screen removes core butts, wedges, etc., and a suction fan removes dust and fines. Vibrating screens may be installed to classify the sand. The amount of suction applied to the system is adjustable and a greater or lesser amount of fines is removed, depending upon permeability and finish requirements.

54. This cleaned sand usually is stored in a bin directly over the mixer into which it is fed as required for the production of facing sand or synthetic sand to be aded to systems or heaps. Where a reclaiming unit is in use, permeability, usually may be controlled by the amount of fines removed with no additions of new silica sand.

General

55. In any application of clay bond, it is important to mix the bond and sand dry before adding tempering water. This results in much higher efficiency from the clay and eliminates the possibility of clay balls being formed by the addition of water to the bond before it has been distributed through the sand.

56. There is also a growing tendency to keep some bonding clay on hand in all foundries even though naturally bonded sand is the principal material used. The bond is used to bolster up weak natural sands, to add strength to facing sands and to build up heaps which ordinarily require excessive additions of new sand. Such a heap would be one in which large quantites of burned core sand fell in to the heap upon shaking out castings or where very heavy castings burned out the sand badly on each pouring. The addition of the necessary amount of new sand to restore strength would result in a large surplus and the daily discarding of enough old sand to make room for the new material. In such cases, clay bond is used in place of new sand or in addition to the use of a reduced quantity of new sand.

TESTING AND CONTROL

57. A. F. A. Reprint 36-26* covers very thoroughly American practice in the testing and control of synthetic as well as natural sands. The methods used are covered in the volume *"Testing and Grading Foundry Sands and Clays"*. Both publications are available through the A. F. A. and probably are available in many English libraries. A few additional comments on testing seem desirable.

58. In testing comparative value of clays, the following conditions are necessary for accurate results:

1. All materials must be carefully measured or weighed.
   (a) The difference caused by careless measuring of several scoops of clay may be greater than the actual difference in strength of materials being compared.
   (b) Different clays vary considerably in weight per unit.
2. All materials must be entirely dry.
   (a) A difference of ½ per cent in water content in a damp silica sand cannot be detected by observation but may account for as much as *18 per cent difference in results.*
   (b) A difference of a few per cent in natural moisture content of a clay may cause up to *30 per cent difference in strength.*
   A fire clay may appear perfectly dry when containing 4 per cent water and a bentonite may appear dry when containing 10 per cent water.
   (c) Moisture content of clay affects strength not only through its replacement of equal quantity of bonding material, but most importantly by its reduction of rate of distribution of the clay.
3. Clays of the same type should be tested at exactly the same moisture content in the sand. The stronger sand will feel dryer and may be too dry for molding. Proper procedure is then to keep moisture the same and reduce

* Reichert, W. G., *"Present Status of Foundry Sand Investigation and Control."*

amount of clay. Common and incorrect procedure is to add water until both batches have the same feel. *Since synthetic mixes get weaker as they get wetter, such water addition destroys the difference in strength which it was intended to measure.*

4. Test specimens should be tested individually as produced to avoid the effect of rapid surface drying.

5. Since variables are unavoidable in large scale foundry tests, final report should average results from at least three batches or mixes.

6. A standard should be run with each test because of the effect of atmospheric conditions. This important precaution is rather universally disregarded.

Sands

59. One important fact, which is not given sufficient consideration in the interpretation of test results, is the relation between various tests. There is too much of a tendency to consider each test by itself. To illustrate this, we will consider only one property: permeability, and the effect upon it of other factors. Some of these factors:

1. Water content.

   Two foundries, each reporting a permeability of 90, might be considered to be operating under similar conditions. If we learn further that one is using synthetic sand with 3.5 per cent water and the other naturally bonded sand with 7.0 per cent water, we immediately realize the difference in practical results. The venting efficiency of a sand obviously depends upon its permeability, which is a measure of its ability to vent gas, and its moisture content, which is the major portion of the gas to be vented. This simple fact is frequently overlooked.

2. Clay content affects permeability in two ways, since increasing clay content reduces permeability, not only because of the amount present but also because of the increased amount of tempering water required. Some types of clays yield much higher permeability

than others, even when present in equal quantity and although the strength of one may be far higher than the strength of the second.

3. Grain size and shape affects permeability in three ways:
   (a) Percentage of voids in sand.
   (b) Percentage tempering water required.
   (c) Percentage bond clay required.

4. Amount of ramming or mold hardness affects permeability, since a hard rammed mold will have lower permeability than one which is softer rammed. Our laboratory test specimen gives relative values but we must think of permeability in terms of actual mold conditions. Dietert gives a formula for determining mold permeability:

$$\text{Mold Permeability} = \frac{H \times P}{h}$$

where:
H = Laboratory specimen average hardness.
P = Laboratory permeability A.F.A.
h = Mold hardness of mold.

5. Thickness of sand in the mold affects permeability in the same manner as hard ramming. The thicker the sand, the higher the permeability which is required and the less informative the relation between laboratory permeability and mold permeability. Dietert gives a formula for determining the reduction in permeability with increased thickness of sand:

$$\text{Venting Permeability} = \frac{25 / \overline{P}}{D}$$

where:
P = Mold Permeability.
D = Depth of sand over pattern in inches.

DISADVANTAGES OF NATURALLY BONDED SANDS

60. Naturally bonded sands, conforming to the description of a more or less ideal sand, are not available in all localities and

the freight cost involved in transporting good sands may make them quite costly. In addition, the following objections are raised against some naturally bonded sands:

1. It is costly to use a sand only until its strength is burned out and then discard all the sand although the grain itself is still good and it lacks only bonding strength.
2. Any naturally occurring product is subject to considerable variation, even when tested and controlled.
3. Most naturally bonded sands have a rather complex grain structure which is not uniform in distribution.
4. Most naturally bonded sands have a rather complex mineral composition and contain impurities from the materials from which derived. On heating, the easily fusible minerals, becoming liquid, attack the more refractory minerals and the melting point of the aggregate is lowered. Naturally bonded sands seldom approach synthetic sand in refractory value, sintering point or durability.
5. All naturally bonded molding sands, and particularly the finer sands, have a high percentage of silt in the portion known as "A.F.A. Clay." This silt reduces permeability and requires a high percentage of tempering water to make the sand reach proper working condition and "feel."
6. Naturally bonded sands are sometimes not available during the winter months and arrive in bad condition when available. It is costly to store a winter supply of sand and, unless kept in heated bins, the sand frequently freezes causing extra expense in preparation for use.

DISADVANTAGES OF SYNTHETIC SANDS

61. Some of the disadvantages of synthetic sands are:

1. Synthetic sands are workable over a narrower moisture range than natural sands.
2. Synthetic sands dry out more rapidly than natural sands.

3. Most synthetic sands require more extensive mechanical equipment than is absolutely necessary for natural sands.

4. There is more difficulty in finishing and patching synthetic sands than is the case with natural sands.

ADVANTAGES OF SYNTHETIC SANDS

62. The advantages of synthetic sands are:

1. They make possible substantial savings. The cost of hauling used sand to a mixer is no greater than the cost of hauling it to the dump. The cost of hauling rebonded sand to the point of use is no greater than the cost of hauling in an equal quantity of new naturally bonded sand. The handling costs cancel out, therefore, and the charges against synthetic sand are the cost of the bond clay, the cost of any silica sand additions and the cost of mixing.

2. Synthetic sands have much greater durability or life than naturally bonded sands and one ton of synthetic sand may maintain strength for 50 to 200 per cent longer than a ton of naturally bonded sand.

3. Silica sands are much more uniform than naturally bonded sands and bonding clays are dependably uniform. Since the foundryman is making a definite mix to fit his own conditions from uniform materials, the result is a much better control over sand conditions.

4. The base sand will be free of silt and the bonding clay will be very low in silt. The fine material in the sand will be almost all active bonding clay. This results in higher permeability, better flowability and considerably less tempering water required.

5. Synthetic sands are almost always more refractory and give higher sintering points than naturally bonded sands. This results in better peel and lower cleaning costs.

6. Being made from simple materials, synthetic sand

is easy to control and American practice shows a sharp reduction in scrap losses with a change to synthetic sand.

7. Synthetic sand, being made as required, eliminates the investment in carrying a winter supply of natural sand in storage and eliminates the difficulties due to such sand freezing in unheated bins.

Magnesium Foundry Practice

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Abstract

In this paper, the authors bring to date the developments in magnesium foundry practice since their contribution in 1935. They have divided their paper into seven parts as follows: (1) Molding sands, which covers the use of both the natural and synthetic molding sands, (2) sand agents, substances used as inhibitors in foundry molding and core sands, (3) cores, covering binders used, the use of inhibitors, typical core mixtures, pasting practice, the use of chills, and storage, (4) molding practice, which describes the use of filters for oxide films, pouring basins and gating and risering, (5) melting practice, including the open flux pot and crucible methods and describing under the latter, type of crucibles and furnaces used, melting procedure, fluxing, heating and pouring, cleaning the crucible, charges, temperature control, and large scale melting units, (6) casting finishing, in which is discussed removal of gates and risers, heat treatment, heat treating furnaces, cleaning methods, and pickling treatments, and (7) alloys, in connection with which a table gives the compositions, characteristics, and mechanical properties of magnesium sand castings.

Introduction

1. Introduced on a practical scale in 1929, the production of magnesium alloy sand castings increased ten fold during the following decade to reach more than a million pounds in 1939, according to government figures. It is estimated that production in 1940 rose to about four million pounds and will more than double again during the current year. At least a score of foundries are casting magnesium, providing convenient availability in all major industrial areas throughout the country.

2. Outstanding characteristic of magnesium castings is, of

* Dowmetal Foundry, The Dow Chemical Company.

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FIG. 1—A 950-LB. MAGNESIUM PUMP HOUSING USED ON A PORTABLE UNIT. THIS IS THE LARGEST MAGNESIUM SAND CASTING REGULARLY MADE IN THE UNITED STATES.

course, their lightness. Cast iron is four times, brass five times, and even aluminum is 50 per cent heavier than magnesium. This light weight, combined with adequate mechanical properties, has led to the use of magnesium castings in a wide variety of applications in which reduction of weight is needed. These include portable tools, textile and packaging machinery, transportation equipment, and large ventilating fans. Largest castings regularly made are 1000-lb. bases and housings for pumps to be mounted on trucks (Fig. 1). Of great national interest at this time, are the many applications in the aircraft industry, the largest consumer of magnesium castings. Here they are indispensable for engine parts, landing wheels, airplane structural fittings, and many accessory and instrument parts (Fig. 2).

3. The sand foundry practice for magnesium alloys is similar in general principles to that used for other metals. However, there are, numerous points of difference, necessitated by the ease of oxidation of magnesium at temperatures above the melting point of approximately 1125°F., a rather high shrinkage (3/16-in. per

ft. when unrestrained) and by the low density of the molten metal, which is slightly more than 1.5 at 1300°F. The first of these characteristics requires that oxidation inhibiting agents be present in the sand and that special fluxes be used in the melting operation. Special methods of gating, venting, and risering castings have been developed to offset the problems due to the high shrinkage and to the light weight of the molten metal. The procedures described on the following pages may be considered to present American practice fairly completely. However, no attempt is made to cover all the operating "kinks" in use in individual foundries, nor to make comparisons with European practice.

Molding Sands

4. Magnesium sand castings are made in "green" sand molds or, less commonly, in "dry" or baked sand molds. The latter are similar to baked sand cores in composition and treatment. Magnesium castings are molded in both natural and synthetic sands. It is desirable that the sand should be as open as possible, consistent with obtaining the degree of surface smoothness required. The more open sand is desirable for two reasons: (1) Magnesium alloys are so light that an open sand permits the metal to flow into the mold cavities with very little back pressure from the air in the mold, and (2) the open sand requires less tempering water and evolves less steam, and also it permits the steam generated to escape quickly, thus decreasing the tendency for reaction between the steam and metal.

Fig. 2—Landing Wheel and Engine Parts Are Typical Magnesium Castings Used for Aircraft.

Natural Sands

5. Natural sands, of the Albany and Champion types, are used in several foundries. The average grain fineness is from 100 to 150 with an A.F.A. permeability ranging from 10 to 25. They contain 10 to 12 per cent clay and require about 6 per cent water for tempering. Foundries operating with natural sand generally use the heap method and recondition their sand with equipment of the aerator type, with only occasional mulling, if any. The high water content of the natural sands results in considerable steam formation as the mold is filled.

6. This fact, combined with poor venting due to low permeability, necessitates the use of rather high quantities of inhibitive agent to prevent surface oxidation or "burning." As much as 10 per cent agent may be added, and this amount may not be adequate on heavy sections. More open sands should be used if any sections more than 2-in. thick are regularly encountered. Misruns, cold shuts, and other casting defects also may be caused by too slow venting of the mold air during the filling of the mold. Subject to the limitations just described, natural sands may be used for the production of light to medium-sized castings.

Synthetic Sands

7. Synthetic molding sand is being used to an increasing extent in magnesium foundries; in fact, it will be used in all of the several larger foundries recently started or being built at this time. The synthetic sands preferably are made from a washed silica base with an A.F.A. grain fineness of 65 to 100, mulled with 3 to 4 per cent bentonite and about the same amount of water. Bank sands also may be used if free from roots, coal, or other organic matter which might cause blows.

8. The sand is conditioned after each use; tempering, mulling, and aerating being done in standard equipment. Care should be taken to remove wood and paper particles as they absorb moisture from the sand and cause blows if contacted by hot metal. Contamination with iron scale or rusty iron particles, such as steel wire and shot, should be avoided, as these will also cause blows.

9. Considerable latitude exists in synthetic sands and the A.F.A. properties shown in the accompanying Table 1 may be considered to be typical of satisfactory sands of various grain sizes.

Table 1

Molding Sand Mixtures for Magnesium Castings

	A	*B*	*C*
Average grain size	100	80	65
Permeability	35-50	60-75	120-150
Bentonite, per cent	4	4	4
Water, per cent	4.5-5.0	3.8-4.2	3.3-3.7
Compression Strength, lb. per sq. in.	6.5	6.5	6.5

The strength will be affected slightly by the kind and amount of addition agent in the sand and greatly by mulling, which should be done thoroughly between each use. The finer sand *A* of Table 1 will give the best casting surface but will possess, to some degree, the disadvantages of fine natural sand as discussed earlier. Very open sands, such as given under *C*, Table 1, while entirely adequate from the permeability standpoint, tend to dry out easily and to give rough surfaces on the castings. The former tendency is overcome in American practice by the use of approximately 1 per cent ethylene glycol in the sand. Smoking of the mold surface is practiced in foundries using such open sands and may be of value in improving the casting surface.

10. In the opinion of the authors, an intermediate sand such

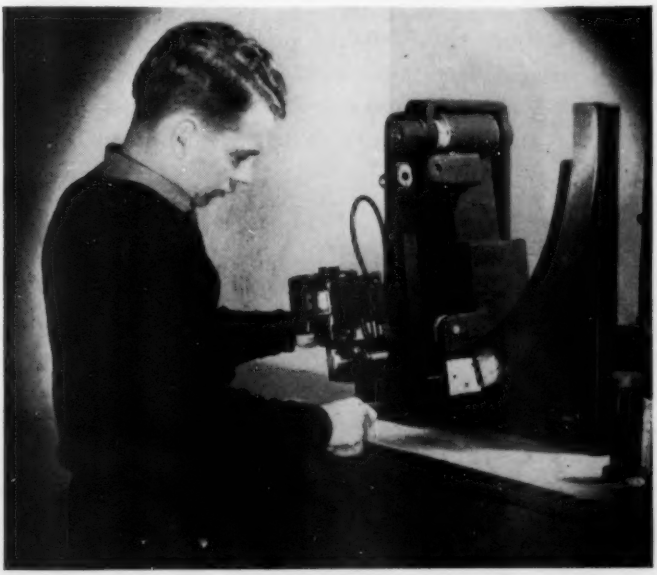


Fig. 8—Sand Control Should be a Routine Procedure to Insure Proper Sand Condition.

as given under *B*, Table 1, is preferable for general use. It yields a fairly good casting surface and has proved satisfactory for castings weighing up to 1000 lb. and for sections up to 8-in. thick. It is easier to work than coarser sands and will stand for considerable variation in ramming conditions.

11. Excessive bentonite causes the sand to become sticky and difficult to work. Additions to the sand will be required occasionally. To avoid lumps in infrequently mulled heaps, the bentonite may be suspended in the tempering water.

SAND AGENTS

12. It is necessary that all green molding sand be treated with a chemical agent to inhibit the action of the water vapor upon the hot metal. The first inhibitors were developed by German foundrymen, who discovered that sulphur and boric acid would protect magnesium-base alloys cast in green sand. Later research in this country has shown that there are a large number of chemicals which will serve as inhibitors. Of these, various fluoride salts are particularly effective. American foundries at present are using combinations of several agents. One is a mixture of sulphuric acid, borax, and sulphur, practically equivalent to boric acid and sulphur in protective value. Better protection, especially necessary with low permeability sands, is obtained by replacing part of the sulphur and boric acid with fluoride salts. Originally ammonium acid fluoride and ammonium borofluoride were used for this purpose, but they have been replaced largely by the cheaper ammonium silicofluoride.

13. In general, the total amount of inhibiting agent will range from 4 to 10 per cent by weight, depending on the sand used and the section thickness of the castings produced. The larger amounts will be required for lower permeability sands and for massive castings. The concentration of agent slowly decreases as the sand is used and more must be added to maintain the proper degree of protection. A convenient control method is to hold the total water-soluble salts, as indicated by a simple analysis, within set limits by the addition of ammonium silicofluoride and boric acid. Powdered sulphur additions are made as indicated necessary by a determination of the CS_2-soluble content of the sand.

Fig. 4—Thin Casting Walls Require That Cores Shall Be Accurately Set in the Molds.

Cores

14. Cores for magnesium castings should be made from an open sharp sand, and should be provided with adequate vents to facilitate removal of hot gases. Most core troubles can be traced to lack of attention to details insuring a minimum of gas evolution or to failure to provide venting of the gas which is formed.

Binders

15. Generally, any good quality core oil is suitable for use, but preference should be given to those forming a minimum of gas. Cereal binders find a limited application. As they tend to absorb moisture, special care is necessary to keep cereal-bonded cores warm and dry before use. In choosing a core binder, consideration must be given also to the ease with which the cores can be removed from the casting, as determined by trial. Ordinary ratings of this characteristic may not apply in casting magnesium alloys,

as the temperature and heat capacity of the light metal surrounding the core is low and the core bond will not be burned out as in the casting of heavier metals.

Use of Inhibitor

16. It is necessary that the core sand be treated with an inhibitor to prevent burning of heavy metal sections. Two types of practice have been developed for obtaining this protection: in one case, low percentages of sulphur and boric acid are mixed with the core sand, while in the other type, the baked cores are sprayed with an aqueous solution of a fluoride. It the latter case, it is necessary to return the sprayed cores to the oven for a short drying period (30-60 min.) after the spraying operation. The fluoride spray is used also on the cores containing sulphur and boric acid where very heavy metal sections contact the core. Additional protection is sometimes obtained by painting parts of cores with a suspension of sulphur in alcohol. This is used to a limited extent however, due to the danger of too heavy a coating of sulphur remaining on the core and causing trouble by bubbles of gas passing through the metal.

Core Mixtures

17. A typical core sand mixture for general use is as follows:

	Parts by Volume
Sand*	1000
Oil	12
Dextrine	8
Sulphur	13
Boric Acid	13

*The sand is a mixture of 40 per cent, with 100 average grain fineness, and 60 per cent with 65 average grain fineness. Moisture content is 6.5 per cent by weight.

18. Standard A.F.A. specimens, before and after baking 2 hours at 420°F. will have approximately the following properties:

Green Compressive Strength, lb. per sq. in.	0.3
Baked Tensile Strength, lb. per sq. in.	120
Hardness	85
Permeability	85

By the addition of more oil, the strength can be raised as desired,

but care should be taken to avoid excessively strong internal cores as they may cause casting cracks. Softer cores may be made by reducing the amount of oil, with, of course, increased fragility and difficulty in handling. The addition of 5 parts (volume) of bentonite raises the green compressive strength to about 1.0 lb. per sq. in. and may be desirable for certain jobs. However, additional oil will be required to maintain the desired baked strength.

Baking Temperatures

19. Cores for magnesium castings should have a minimum of oil and should be baked thoroughly. The temperature of baking will be dependent on the oil, but generally will be between 400 and 450°F. Driers are used extensively, due to the high dimensional accuracy required in aircraft castings.

Pasting Practice

20. The cores are necessarily soft and to facilitate pasting, the joining surfaces are painted with a 1 to 3 shellac-alcohol solution to give a stronger surface. Care is taken that the paste does not come through to the surface of the core with resultant danger of a blow. Joint lines and shallow surface defects may be smoothed with the following mixture, made up to a soft paste with denatured alcohol containing a little lubricating oil for bond:

Talc	25 parts
Sand (200 mesh)	75 parts
Sulphur	2 parts
Boric Acid	2 parts

The area is thoroughly dried by torch or by returning the core to the oven.

Chills

21. Chills are placed in the cores where necessary and may be either of the round button type or formed to fit the contour of the casting surface. Cast iron generally is used, as it is cheap and does not alloy with molten magnesium. The greatest objection to copper-base chills is the contamination of melts from chills adhering to scrap castings. Some operators prefer to score the face of the chill to avoid blows, but this does not appear to be necessary if precautions are taken to prevent condensation of moisture on the

chill. This is best accomplished by the use of some type of a coating, which must be thin and contain no material which will give off gas upon contact with the hot metal. A suspension of talc in alcohol containing 1 oz. per gallon of either "Mazein" or rosin makes a satisfactory coating material. It is necessary that the chill be clean and free from any rust or moisture.

Storage

22. Cores which do not go directly from the baking racks and assembly benches to the molding floor, are stored in a room which is maintained at a temperature of at least 100°F. This insures that the cores will be thoroughly dry when placed in a mold and eliminates the foundry troubles incident to damp cores.

MOLDING PRACTICE

23. The molding of magnesium alloy castings is probably the most important single phase of the entire foundry procedure. While it is desirable in the founding of all metals that the mold should be so constructed that the metal will flow into the mold cavity smoothly and with a minimum of turbulence, it is of vital necessity with magnesium alloys and deviation from this basic foundry rule will result in scrap castings. Excessive turbulence in the metal stream, from the time it leaves the melting unit until the metal has reached its final place in the casting, will cause oxide skins to become mixed with the metal. These oxide skins, being of about the same specific gravity as the metal, do not separate from the metal but are swept into the casting where they tend to rise to the cope side and appear after sandblasting as surface defects. In addition to the surface defects caused by the oxide skins, a further result of turbulence in the metal stream is the entrapping of bubbles of air, which also tend to rise to the cope surface and are opened during cleaning operations and appear as blows or gas holes.

Filters for Oxide Films

24. To avoid turbulence in the mold, the casting should be gated in such a way that the metal will be brought into the mold cavity at the lowest point and the gates so arranged that the sprue can be filled as quickly as possible after pouring starts. Filters placed at the bottom of the sprue are very effective aids in keeping out oxide skins and smoothing out the metal flow. Two types of

filters used are: (1) perforated skim gate, and (2) steel wool. To be effective, either of these materials should be placed at the bottom of the sprue or in the horizontal runners in such a way that the metal must flow through them on its way into the mold cavity.

Pouring Basins

25. Of vital importance in the proper filling of the mold, is the use of a correctly-designed pouring basin. This may vary in size from small cast iron ones used on bench molds to large ones made of green sand for large floor molds. The basin must always be long enough and deep enough to allow the metal stream to enter without direct impingement on the sprue and to permit the metal to quiet down before entering the sprue.

Sprues

26. Two types of sprues are used, round and rectangular slots. The round sprue is molded more easily and is commonly used in conjunction with the perforated skim gate. The rectangular slot sprue is claimed to decrease turbulence because of the prevention of any swirling tendency of the metal. It is used either without any filter material or with steel wool. In any case, the sprue must be of such a size that it can be choked easily so that all the opening from the bottom gate up into the pouring basin can be filled quickly to prevent oxide skins being washed down the sprue and into the casting.

Gating

27. The casting should be filled through a number of gates rather than a few large ones. This is desirable to avoid overheating of the sand at the gates and because molten magnesium loses its heat so very rapidly that any attempt to flow metal any great distance through a thin casting section will result in misruns. A common type of gating is to place a ring runner completely around the casting with a number of gates entering the casting uniformly around its circumference. Adequate vents should be provided from the tops of runners to prevent building up pressure in the mold passages. This is especially important in molds which are poured rapidly at high temperatures.

Risers

28. Risers are used freely to insure the soundness of heavy sections of castings. Because of the light weight and low heat content of the metal, it is necessary that the riser be connected as directly as possible to the section to be fed. It sometimes is found to be good practice to place a riser over a gate to hold up shrinkage in a section which is difficult to feed by direct risers.

29. Compared to the practice with many other metals, the risers required for magnesium alloys are much larger and greater in number. The castings, shown in Figs. 5a, 5b and 5c, are fairly typical of the procedure followed on magnesium castings.

Chills

30. Chills frequently are used to equalize the freezing of heavy and light sections. After each use, the chills are thoroughly heated in a core oven to 400-425°F. They are then sandblasted and sprayed while hot with the chill coating solution described under the section in which cores are discussed. They are kept in a warm place until ready for use, but are allowed to cool to room temperature just before placing in the mold, which is closed and poured as soon as possible.

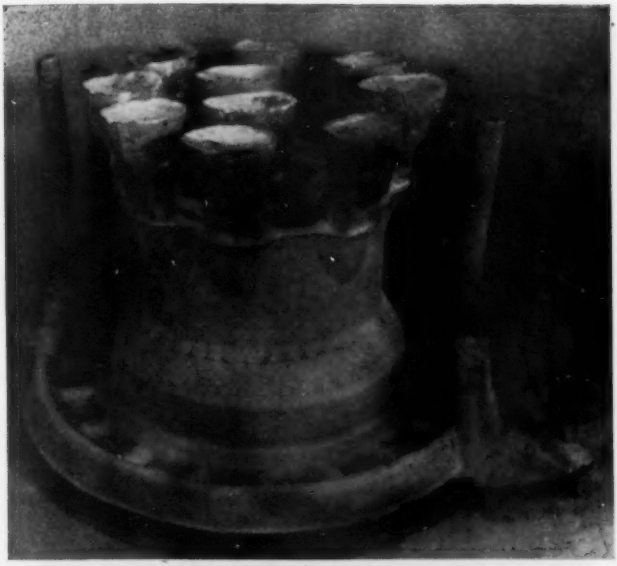
MELTING PRACTICE

31. Magnesium alloys for sand castings are melted by two methods, the open flux pot and the crucible. The former method uses a relatively large amount of fluid chloride-base flux (10-20 per cent of the metal weight) at the bottom of a large, cast steel, stationary pot. The flux serves the dual purpose of cleansing the metal and protecting it from oxidation. The metal is hand dipped in ladles holding up to 25 lb. The present use of this method of melting is limited to the production of small castings and to cleaning and reclaiming scrap. It has been described in detail by Gann and Brooks[1]. The crucible method, using individual melts, is used much more generally, as it is more adaptable to pouring large castings and to usual foundry production methods.

Crucibles and Furnaces

32. The crucibles ordinarily are made of low carbon steel.

[1] Gann, J. A., and Brooks, M. E., *"Founding Magnesium Alloys,"* TRANSACTIONS, American Foundrymen's Association, vol. 43, pp. 591-614 (1935).



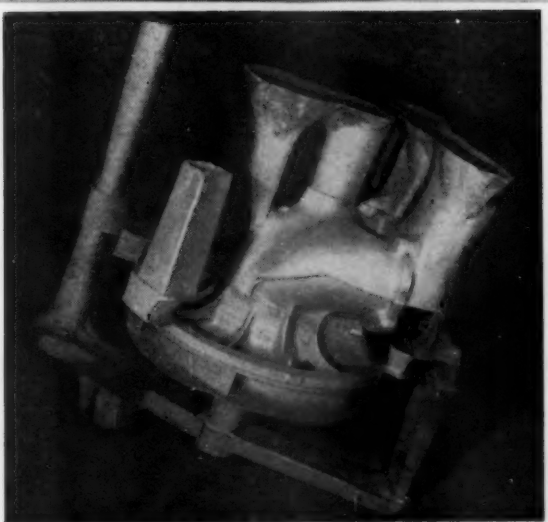


Fig. 5A (Top), 5B (Center) and 5C (Bottom) Castings Showing Gating and Risering Practice on Magnesium Castings.

A "fire-box" grade of steel may be desirable for the larger sizes. The crucibles are used without lining as iron is almost insoluble in molten magnesium, even at 1600°F. The crucibles in current use range from 60 to 600-lb. capacity and are heated in oil or gas-fired furnaces. Up to a total weight of about 200 lb. (120 lb. of magnesium alloy) the crucibles are carried to the molds manually or on small buggies, as shown in Fig. 6. Above this weight, monorail conveyors and cranes are used to transport the metal.

Crucible Inspection

33. It is desirable that the furnace design and the combustion control be such as to minimize the scaling on the outside of the crucibles. Crucible settings are cleaned daily to insure that no accumulation of oxide occurs. If molten magnesium from a leaking crucible comes in contact with hot iron scale, a violent reaction of the thermit type may result. The crucibles are examined frequently, at least every 8 hours, and are discarded if thin spots are indicated by hammering. Scaling is the usual cause of crucible failure, and in the interest of economy and safety, consideration is or should be given in every foundry to methods of controlling it.

Types of Crucibles

34. Non-scaling stainless steels containing considerable nickel cannot be used for crucible construction because of the resulting contamination of the melt with nickel. High chrome iron (28 per

FIG. 6—MOLTEN MAGNESIUM IS TAKEN TO MOLDS IN RUBBER-TIRED BUGGY.

cent chromium) has been used to some extent and is satisfactory from the scaling standpoint. In the absence of scaling, mechanical distortion and weld cracking, due to prolonged exposure to high temperatures, govern the useful life of the crucible. At the moment, the cost of the high-chrome iron crucibles does not appear to be justified. Data are not available on the performance of chrome irons with lesser amounts of chromium or on carbon steels clad with non-scaling material on the exterior.

35. While not a factor with ordinary steel crucibles, there is some indication that pitting or corrosion on the interior by melting fluxes may affect the performance of long life crucibles. Silicon carbide crucibles can be used but are not handled as conveniently as the steel crucibles. However, they are necessary if it is desired to cast magnesium alloys with less than 0.020 per cent iron contamination. Clay or clay-bonded refractory crucibles should not be used because of attack by the molten metal and fluxes.

36. At present, the most practical solution of the scaling problem appears to be the use of low carbon steel crucibles with the outer surface calorized or aluminum-sprayed, sealed and annealed by the Metcoseal process or its equivalent. Satisfactory results also have been obtained by dipping freshly sandblasted steel crucibles in molten aluminum for 20 minutes at 1500°F. Crucibles coated with aluminum by any of these processes do not scale but are discarded after 250 to 300 heats because of distortion, and thus give three to four times the life of ordinary steel crucibles.

Crucible Melting

37. In the crucible method of melting, protection of the magnesium alloy from oxidation is by the use of a special flux (Dow Flux No. 31) which is fluid when first melted but which becomes dry and crusty after brief exposure to high temperatures. In melting down, the usual procedure is as follows: A light sprinkle of flux is placed in the crucible, which then is charged with ingot and scrap metal. As the metal is charged and during the melting process, flux is dusted on the surface in such quantities as are needed to prevent burning. The amount of flux required during this operation is small but it is essential that the molten metal, as it wells up in the crucible, should be kept dusted with a light layer of flux. If this is not done, considerable burning will take place with resultant loss of metal and fouling of the melt and crucible walls with oxide.

Fluxing

38. After the metal is melted, and at a temperature not exceeding 1300°F., the melt is stirred. This operation is performed with a 1-in. iron rod bent in the form of an "ell" with the short leg approximately the depth of the crucible. This stirring rod is moved in the crucible in such a manner as to give a rotational motion to the melt. During the stirring operation, flux is added in sufficient quantity to form a fairly heavy coating on top of the melt. The stirring causes the flux to wet the oxide particles in and on the melt, thereby making them heavier and causing them to separate and sink to the bottom of the crucible. If the stirring and fluxing have been properly done, the metal surface will have a clear silvery luster. If it appears dull or frothy, the dross and flux should be removed from the surface of the melt with a skimmer and the stirring repeated with fresh flux.

Heating and Pouring

39. After the stirring is completed, the thermocouple is inserted and the surface of the melt is covered carefully with flux, particular attention being given to the area where the surface of melt contacts the crucible wall and around the thermocouple. It is necessary that the melt be well covered with flux at this stage to prevent burning during the subsequent heating period. The crucible contents are then heated to approximately 1600 to 1650°F. and allowed to cool to the casting temperature, which generally is between 1400 and 1600°F. The superheating operation refines the grain and thereby improves the mechanical properties of the alloy. It is very important that flux should not be used on the metal too short a time before casting. If the flux has not had time to thicken and dry, it may flow out with the metal and cause detrimental inclusions in the casting.

40. After the crucible is ready for casting the surface of the melt is cleaned by carefully spudding away and removing the scale of flux and oxide from the pouring lips and the surface of the melt. The metal burns readily at this temperature (1400 to 1600°F.) as soon as the protecting flux layer is removed. Burning during the cleaning of the melt and the pouring of the casting is controlled by dusting on the surface of the metal a powder containing 80 per cent sulphur, 17.5 per cent boric acid, and 2.5 per cent ammonium borofluoride.

FIG. 7—POURING A LANDING WHEEL WITH TWO CRUCIBLES.

41. It is standard practice in some foundries to add 0.05 per cent metallic calcium to the crucible just before the metal is poured. Calcium helps prevent surface oxidation of the casting in the mold if the agents in the sand do not adequately protect the metal. The calcium also may afford some protection during heat treatment. The amount added is controlled carefully because more than a few hundredths of a per cent slow up the rate of solution heat treatment.

Cleaning the Crucible

42. After the casting has been poured, the crucible is returned to the melting floor and cleaned preparatory to charging for the next melt. If proper casting practice has been followed, a layer of molten metal about 2 or 3-in. deep has been left in the bottom of the crucible. This residual metal is desirable for two reasons: (1) The danger of pouring flux with the metal is much less if the crucible is not drained, and (2) the presence of molten metal facilitates melting down the next charge. The side walls of the crucible are spudded down and the dross removed from the surface of the melt and the bottom of the crucible by means of suitable tools. During this cleaning operation, sufficient flux is

sprinkled on the metal to prevent burning. The crucible is now ready to charge for the next cycle of operations.

Charges

43. The normal consumption of flux in the crucible melting method is between 2 and 3 per cent of the weight of the metal melted. The crucible charge may consist of either 100 per cent virgin ingot, 100 per cent scrap, or a mixture of both. If the melting operation is properly carried out, the properties of the resulting castings will be independent of the nature of the charge. Usual foundry practice is to use about 40 per cent ingot and 60 per cent scrap for each melt. Scrap for use in the crucible should be clean and free from metal screens and adhering sand. The latter might result in increased silicon content, as sand is reduced by molten magnesium.

Temperature Control

44. Accurate melting and pouring temperature control is necessary, and this is secured by the use of either chromel-alumel or iron-constantan thermocouples in mild steel protection tubes immersed in the melt. The crucible is cooled in the furnace or is removed from the furnace above the desired pouring temperature and allowed to cool in the pouring shank until ready.

Large Scale Melting Units

45. During the past year, the increases in magnesium foundry production have stimulated the development of large melting units of 1000 to 2000-lb. capacity, from which metal is poured into small individual crucibles at about 1300°F. The small crucibles then are placed in their furnaces, fluxed and brought up to temperature as described earlier. Ingots and scrap are melted together, the large size of the batch permitting improved composition control. Production from the small crucibles also is speeded up as they are charged with metal already melted. These large units are oil or gas-fired and are of both center-tilting and nose-tilting types. The melting pots are of heavy wrought steel construction similar to the small crucibles. Protection from oxidation is secured by the use of flux. Additional developments can be expected as experience is gained in the operation of these units.

Casting Finishing

Removing Gates and Risers

46. After cooling for a safe period following the pouring, the castings are shaken out by hand or on vibratory screens. The cores are removed by vibrating and with hand and air tools. After sand blasting, the gates and risers are cut off with metal-cutting band saws having four teeth per inch and running at 8000 ft. per min. The sawdust is swept up frequently to minimize the possibility of ignition by occasional sparks from the saw. The gates and risers from very heavy castings may require removal by air chisels. Lathes and other machine tools also are used to remove gates and risers not easily accessible for sawing.

Heat Treatment

47. If heat treatment is desired, this usually is done before the final cleaning operations. The castings are brought up to the solution heat treating temperature in not less than 2 hours, left for the specified total time, removed and cooled in air. The temperatures and total times for the two common magnesium sand casting alloys are as follows:

H — 12 hours at 730°F.
C — 20 hours at 760°F.

Slightly higher temperatures may be required if calcium has been used in the casting operation.

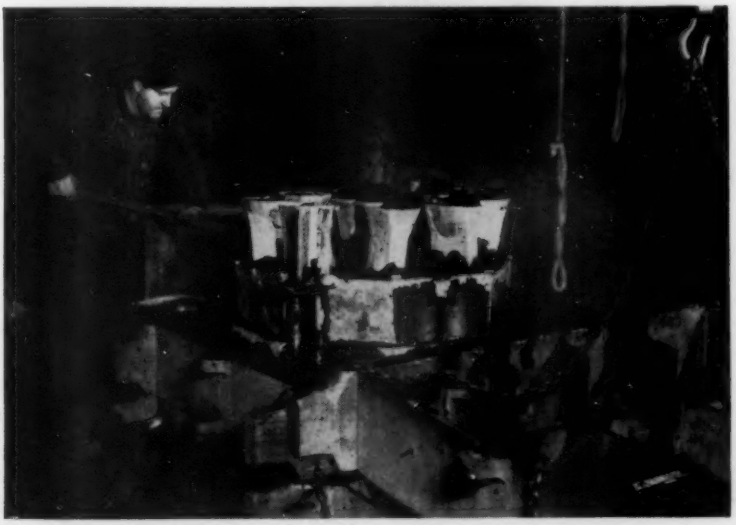


Fig. 8—Shaking-out a 160-lb. Landing Wheel Casting.

FIG. 9—HIGH-SPEED, COARSE-TOOTH BAND SAWS ARE USED FOR TRIMMING OFF GATES AND RISERS.

48. The solution heat treatment increases the tensile strength and elongation and is particularly desirable for parts requiring shock resistance, such as airplane landing wheels. If increased hardness and high yield strength are required, even at a sacrifice of elongation, these may be secured by an aging treatment of 16 hours at 350°F., following the solution treatment. Aircraft engine parts frequently are used in the heat treated and aged condition.

Heat Treating Furnaces

49. Circulating atmosphere, electric or gas-fuel furnaces are used for the heat treatment of magnesium castings. Direct gas-firing is not recommended for temperatures above 740°F. Indirect gas-firing should be as satisfactory as electric heat from the standpoint of atmosphere control but might be less simple mechanically. For temperatures up to 800°F., SO_2 has proved to be a satisfactory inhibitor of surface oxidation at a concentration of approximately 0.5 per cent. From preliminary tests, the use of an atmosphere made by the controlled combustion of natural gas followed by dehydration appears to be a possibility.

Cleaning

50. The cleaning room operations consist of grinding, filing and buffing. The remainder of the gates and risers are ground off smooth with the casting surface and as much of the general cleaning operation is done on the grinding wheels as is possible. Surplus metal, fins, etc., which are inaccessible to the grinding wheels are removed with rotary filing tools. These rotary files are mounted on flexible shafts and rotate at speeds up to 3500 r.p.m., the smaller diameter tools running at the higher speeds.

51. In some castings, it is required that the entire surface be finished by grinding and polishing. This is usually done on buffing wheels to the surface of which has been glued abrasive powder of different grades. The grinding and polishing is done on machines which are equipped with dust-collecting systems, preferably in-

Fig. 10—Rotary Files Are Used for Cleanup Work.

dividual, so arranged that the magnesium dust is wetted immediately with a heavy water spray and is stored under a large excess of water. Final disposition of the sludge should be by burying after dilution with earth or old core sand.

52. Castings frequently are pressure tested with air or water to determine their tightness for certain applications. While improved gating and risering methods will go far in securing tight castings, occasional recourse to impregnation is necessitated by the design of particular castings. A satisfactory impregnation method includes vacuum-pressure treatment with tung oil. The oil is later polymerized to an insoluble solid within the microscopic pores of the casting by heating the casting to 475-500°F., for a short time. Some alloys are less subject to intercrystalline shrinkage then others and, therefore, make it easier to produce pressure tight castings. For this reason, preference is sometimes given to the composition represented by *C* in Table 2, especially for engine castings.

Pickling Treatment

53. After the castings have been completely cleaned, they are re-sandblasted to give a uniform surface appearance. They are then given a pickle of approximately one minute in a 2 per cent sulphuric aqueous solution, a water rinse and a one-minute immersion in a chrome-pickle bath, followed by rinses in cold and hot water. The chrome-pickle solution contains 1.5 lb. of sodium dichromate and 1.5 pints of concentrated nitric acid per gallon. This treatment affords protection against corrosion during storage and provides a suitable paint base for subsequent painting.

ALLOYS

54. The bulk of the magnesium sand castings produced in this country are made from the two compositions listed in Table 2. They appear to be meeting most of the service requirements put upon them in an increasingly wide range of applications. However, new compositions can be expected to be developed in response to changing needs. As an example of such development, methods have been perfected for the control of iron contamination in the casting alloys listed in Table 2 to less than 0.005 per cent. If other and more easily controllable impurities also are held to low values, the salt water resistance of magnesium alloys is remarkably good and applications formerly considered impractical become possibilities.

Table 2

COMPOSITIONS AND CHARACTERISTICS OF MAGNESIUM SAND CASTINGS

		Chemical Compositions—Per Cent							
Alloy	A.S.T.M. Alloy No.	Aluminum	Manganese	Zinc	Silicon	Other * Impur. Max.	Magnesium	Characteristics and Uses	
C	17	8.3-9.7	0.10 min.	1.7-2.3	0.5 max.	0.3	Remainder	As cast	For castings requiring moderate strength and toughness.
								Heat treated—HT	For castings requiring high strength and best toughness.
								Heat treated and aged—HTA	For castings requiring high yield strength and hardness.
H	4	5.3-6.7	0.15 min.	2.5-3.5	0.5 max.	0.3	Remainder	As cast	For castings requiring moderate strength and toughness.
								Heat treated—HT	For castings requiring high strength and best toughness.
								Heat treated and aged—HTA	For castings requiring high yield strength and hardness and moderate toughness.

* Copper, max. 0.05 per cent. Nickel, max. 0.03 per cent.

NOTE: Alloy C is used for maximum pressure tightness and Alloy H is used for best salt water resistance.

MECHANICAL PROPERTIES OF MAGNESIUM SAND CASTINGS

Alloy	Condition	Tensile Strength, lb. per sq. in.		Yield Strength [1], lb. per sq. in.		Elong. in 2-in., Per Cent		Compressive Strength lb. per sq. in.	Shear Strength lb. per sq. in.	Rockwell "E" Hardness	Brinell Hardness	Impact Izod, ft.-lb.	Fatigue [2] Endurance Limit, lb. per sq. in.
		Typical	Specified Minimum	Typical	Specified Minimum	Typical	Specified Minimum						
C	As cast	24,000	20,000	14,000	10,000	2	1	51,000	.....	68	60	1	11,000
	Heat treated	39,000	30,000	14,000	10,000	10	6	52,000	.....	68	59	4	11,000
	Heat treated and aged	39,000	32,000	21,000	18,000	3	1	58,000	.....	85	77	1	11,000
H	As cast	27,000	24,000	12,000	10,000	5	4	45,000	16,000	59	55	3	10,000
	Heat treated	38,000	30,000	12,000	10,000	11	6	46,000	16,000	60	55	5	10,000
	Heat treated and aged	38,000	32,000	19,000	16,000	5	2	50,000	18,000	74	70	2	10,000

[1] Yield strength is defined as the stress at which the stress-strain curve deviates 0.2 per cent from the modulus line.

[2] Fatigue endurance values are obtained on R. R. Moore machines and are based on 500 million cycles.

DISCUSSION

Presiding: JOS. SULLY, Sully Brass Foundry, Ltd., Toronto, Ont.

MEMBER: Would Mr. Brooks tell us something about their process of eliminating leaky castings.

MR. BROOKS: We are using Chinawood oil or tung oil for the purpose of impregnating castings which it is impossible to make pressure tight by the best foundry practice. There are some castings, the design of which is such that it is just impossible to gate and riser in such a way to make them perfectly sound. These castings we impregnate with tung oil, which gives a permanent seal against leakage.

The process is as follows: The castings are placed in an autoclave, which is so designed that it will stand a high vacuum and pressure of about 100 lb. sq. in. When the castings are put in, they must be thoroughly dry. Then the autoclave is sealed and as perfect a vacuum as possible is put on, at least 28-in. of mercury, and left on for 10 or 15 min. Then the hot tung oil at about 210°F. is brought in to cover the castings. After the castings are covered with the oil, they are subjected to 75 to 100 lb. air pressure for about 10 min. Then the pressure is taken off and the castings are removed from the tung oil bath, rinsed in kerosene and then placed in an oil bath which is maintained at a temperature of about 475 to 500°F. They are left in the hot oil bath for 30 to 45 min., are then taken out and rinsed in kerosene and are ready for the test. Sometimes they are soaked in kerosene after that impregnation.

During the evacuation process the air which is in the pores of the castings is sucked out, leaving a vacuum in those pores. Then as the hot oil goes in and the pressure is put on, the oil is forced into those pores. When the casting is taken from the tung oil bath, those pores are full of liquid tung oil. Then during the heating process in the hot oil bath at about 475°F., the liquid tung oil is polymerized to a solid and remains a solid indefinitely. We know of castings that were impregnated several years ago and gave service during the entire life of the casting without any indication that they had opened up.

MEMBER: What is the effect of the dichromate pickle?

MR. BROOKS: It has no effect on the impregnation. Any appreciable amount of surface etching may open up other pores not open when the impregnation took place. That is the only action which would cause any harm.

H. M. LANE[1]: Tung oil has a definite point at which it polymerizes and becomes solid and beyond that point you cannot break it down. The varnishes and enamels are simply tung oil fluxed with rosin. You must be careful to keep rosin away from the tung oil that you are going to use for this purpose. If you have pure tung oil with a definite point at which the breakdown takes place, it will always assure you of a hard product which cannot be redissolved.

[1]Consulting Engr., Grosse Ile, Mich.

MR. BROOKS: I would like to add another point to this tung oil impregnation and that is the necessity of treating the tung oil with an inhibitor. The inhibitor is about 2 ounces of hydroquinone per gallon. If that is not done, the tung oil will set up during the first few runs in the impregnator. If it is properly inhibited, it will last a long time.

MEMBER: Would Mr. Brooks care to discuss the effect of gas firing versus oil firing?

MR. BROOKS: As far as we have ever observed, there is no effect due to furnace atmosphere during the melting of magnesium. We melt our metal in oil-fired furnaces and I know of foundries where they melt with gas; and one foundry where they melt with electricity. As far as any of our observations or tests have gone, there is no effect, under normal operating conditions, of any furnace gas on the metal.

D. V. LUDWIG[2]: Do you find any difference in heat treating the alloys between the electric, gas or oil-fired furnaces? Would the furnace atmosphere in gas or oil-fired furnaces make any difference in the quality of castings when heat treated, as compared with the electric-fired furnace?

MR. BROOKS: No, we heat treat in both gas and electric-heated furnaces. I do not know of anyone who is using an oil-fired furnace. So far as the effect of the atmosphere in the heat treating furnace on the properties of the metal, we have never observed any difference. There is a feeling that at the higher heat treating temperatures necessary for one of the newer alloys, that heat treating in a gas furnace introduces a possible fire hazard which is not present in the electric furnace. Our experience does not confirm that. We have not had any trouble.

MR. LUDWIG: I read that there was some question about basic atmospheres in the furnaces as against acidic atmosphere in gas fired furnaces. The article stated that acidic atmospheres, with free sulphurous acid, were desirable in heat treating magnesium base alloys, whereas a basic atmosphere was undesirable. The statement I read was that the basic atmosphere created an inter-crystalline corrosion, or surface corrosion condition, in the heat treated parts.

MR. BROOKS: We have always felt that the presence of basic conditions in contact with hot magnesium, whether it was molding sand, heat treating furnaces, or any place, tended to promote burning. We have definite knowledge of that in molding sand. The use of about 0.5 per cent sulphur dioxide in a heat treating furnace atmosphere, is common practice and does inhibit surface oxidation.

MEMBER: I heard that some of the aircraft companies, instead of using the tung oil process, are using sodium silicate. What is the disadvantage of using that against the tung oil?

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[2]Metallurgist, Sperry Gyroscope Co., Inc., New York, N. Y.

MR. BROOKS: We used sodium silicate a number of years ago and did not have very good results. We changed over from the sodium silicate to the tung oil because we did not believe the sodium silicate was as permanent and did not give as good results.

W. JEWETT[3]: With the National Defense Program stepping up the production of the foundries, I would like to know if anything has been attempted in the country in the way of conveyorizing molding magnesium castings? Has anything been done towards using the conveyor system and, if so, what might we expect to encounter and have to overcome in the use of this method.

MR. BROOKS: We use a small conveyor for moving small molds to the pouring station. We have not done very much with the larger molds on conveyors. That is a matter of mechanical production but I do not believe there would be any peculiarities in conveying magnesium. There is one large foundry, going into operation at the present time, which is going to be highly conveyorized. Just how it is going to work out, we do not know. I do not believe there is anything other than the possible distortion of the mold due to the settling of the heavy cores during the moving by the conveyor that would cause trouble. We have to work to close tolerances and cannot have very much settling.

CHAIRMAN SULLY: What are the particular dangers that you have to look out for in the casting of magnesium?

MR. BROOKS: Magnesium in the molten state is very easily oxidized and if anything with moisture in it, such as the ingot which is moist, or any of the tools which have laid around and picked up any moisture, come into contact with the molten metal, there is very likely to be a blow. The tools used around the melting floor are more likely to be damp than tools used on another metal because the flux used is hydroscopic. Of course, the tools have all been in contact with the flux and if they lie around for a few hours, or over night, in a comparatively cool place, they may pick up moisture. If a man uses one of the damp tools on a pot of molten metal a violent explosion will occur. In pouring a mold, sometimes a damp core or wet molding sand will cause a pop back up out of a sprue or riser.

It has been our experience that most of our melting accidents have been clothing burns started by spatters of molten metal. We have had relatively little trouble with metal burns directly. We now furnish fireproof woolen shirts, a face mask, which is fire-proof, and a leather chap which covers them from the waist down and which sheds molten metal. By requiring the men to use this equipment, we have had very little trouble from burns.

R. R. WEBER[4]: Would small additions of calcium just before pouring prevent burning?

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[3]Plant Engr., Bendix Aviation Corp., Bendix, N. J.
[4]Chief Chemist and Met., Wright Aeronautical Corp., Paterson, N. J.

MR. BROOKS: You are referring to surface burning or oxidation during the casting operation. There is a difference of opinion in this country on the use of calcium in magnesium. It happens that our company does not use it. According to our tests, the primary reason for the necessity of using calcium, is to supplement the protection which is put in the molding sand. When using fluoride-base inhibiting agents, as described in paragraphs 12 and 13 of our paper, calcium does not appear to be necessary. If other common agents are used, some trouble may be experienced with burning on heavy sections. The presence of calcium does prevent burning under these conditions.

MR. WEBER: Does it help create cracks in castings?

MR. BROOKS: That is a question on which I would like to have a definite answer. We have done some experimental work with calcium, and it may be just a coincidence, but on two or three different occasions when using it, we ran into a siege of cracks. However, we never were completely satisfied that the calcium was the primary cause of the cracks.

MR. WEBER: Do small amounts of lead and tin have any effect on the heat treatment of this alloy?

MR. BROOKS: No, not ordinary quantities of impurities. In all the sand casting alloys, the A.S.T.M. specification allows up to 0.3 per cent total impurities. The presence of up to 0.2 per cent of either lead or tin causes no trouble. I believe you could go higher, although we have not actually checked that. Tin, I am very certain, would not cause any trouble.

R. E. WARD[5]: The author mentioned pouring temperatures of between 1400 and 1600°F. In the case of many castings, it is possible to pour at a temperature of between 1300 and 1400°F., perhaps down near the 1300°F. end of the range. I was wondering if there were any disadvantages or difficulties to be expected in pouring at the lower temperature? Would there be a finer grain at that temperature, greater porosity or greater drossing?

MR. BROOKS: The drossing of the metal at the lower temperature would be definitely less. As to the question of the grain size, I doubt if there would be enough difference to be able to see it. The primary cause of the fine grain is the super-heating. If a metal has been superheated, the grain will be fine, unless the pouring temperature is high, say about 1600°F. Just where the break-over is, I am not certain. I believe the statement was made in the paper that the usual pouring temperatures were between 1400 and 1600°F. Probably 95 per cent of the metal poured in our foundry is poured at between 1500 and 1600°F. There are very few castings of the type now made that will run at 1300°F. The aircraft engineer continually wants thinner and thinner

[5]Metallurgist, Bendix Aviation Corp., Bendix, N. J.

sections and more complicated castings, so the pouring temperature has been going up. We pour at as low a temperature as we can and consistently fill the mold and avoid mis-run trouble.

MR. LUDWIG: Have you met any particular trouble from flux inclusions, that is, the chloride flux in the castings? I have noticed that a number of our suppliers have had troubles with flux spots in the casting which cause corrosion, even after the material has been cleaned and dichromated and shipped. There is a little bit of moisture and it will break out. We test with silver nitrate and it indicates the fluoride. Have you had that trouble and if you have not, how have you licked it?

MR. BROOKS: Yes, we have run into it. It is a trouble that can be eliminated almost entirely by careful attention to the proper melting and pouring technique. If the metal is not stirred properly in the crucible and the flux is not used correctly, flux contamination may occur. But, given the proper knowledge and the proper attention to detail, flux inclusions can be eliminated.

MR. LUDWIG: No particular technique is necessary outside of that regularly required?

MR. BROOKS: Just be very careful that you do it right. That is the only precaution. You mentioned that the dichromate treatment did not remove the flux inclusions. The dichromate treatment will not completely kill the flux inclusions. If there is a small flux spot, the dichromate treatment will remove it from the surface but will not completely nullify the bad effects. If any flux remains, it is going to break out again.

MR. LUDWIG: We have had occasions, with large castings, where we have dichromated them and they have broken out and we have sandblasted them and redichromated them and they have broken out again.

MR. BROOKS: Sometimes, when the surface contamination is very slight, an extra dichromating treatment will remove it, but if the inclusion is really imbedded in the metal, it cannot be removed by any surface treatment.

MR. WEBER: Is alloy *C* less susceptible to intercrystalline shrinkage than alloy *H*?

MR. BROOKS: Yes, it is very definitely. Alloy *H* is 6 per cent aluminum and 3 per cent zinc. Alloy *C* is 9 per cent aluminum and 2 per cent zinc. Alloy *H* has been used for castings for a number of years and alloy *C* has just come into use during the past year. The reason for its being adopted is that it is easier to make a sound casting with it than it is with alloy *H* because it is less susceptible to intercrystalline shrinkage. There is some indication that alloy *C* is less sensitive to variation of riser size than alloy *H*. It is definitely indicated that it is easier to get sound castings with alloy *C* than it is with alloy *H*.

Centrifugal Casting and Equipment

By Nathan Janco*, Tulsa, Okla.

Abstract

The vertical type centrifugal casting machine is discussed herein. According to the author, the practicability of centrifugally casting a part is determined by the distribution of metal sections. Metal is introduced in vertically cast centrifugal castings through a single opening which serves both as a gate and head. Desirable characteristics in vertical centrifugal casting machines are variable speed, rigid construction, easy method of loading and unloading machine, a brake for rapid deceleration and safety features. The number of machines required for a given production is dependent upon the time consumed in casting each mold. Spinning time in the machines described varies from 2 to 10 minutes. Centrifugal castings can be made in green or dry sand molds. Various methods used to fasten such molds to the table of the machine are listed. The author shows how a savings can be made due increased yield of centrifugal over static castings.

1. There are essentially two types of centrifugal casting machines—the horizontal type which rotates about a horizontal axis, and the vertical type which rotates about a vertical axis. The horizontal centrifugal casting machines used to make pipe, bushings and cylindrical objects are well known. The range of application of vertical centrifugal casting machines is considerably wider, but not so well known. Therefore, this discussion will deal exclusively with vertical centrifugal casting machines. Castings which are not cylindrical, or even symmetrical, can be made in this type of machine.

Gating Practice

2. The practicability of centrifugally casting a part is determined by the distribution of metal sections. A short discussion of the gating involved will help clarify this. In its usual and simplest form, the gating of centrifugal castings utilizes a single gate, which combines the function of gate and head. The last

* The Centrifugal Casting Machine Co.

Note: This paper was presented at a Plant and Plant Equipment session during the 45th Annual A.F.A. Convention, May 15, 1941, New York City, N. Y.

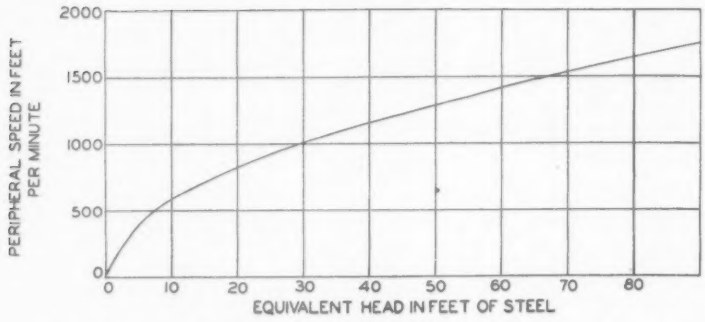

FIG. 1—GRAPH SHOWING RELATIONSHIP BETWEEN PERIPHERAL VELOCITY AND THE EQUIVALENT HEAD OF A CENTRIFUGAL CASTING.

part of the metal in the mold cavity to solidify should naturally be the gate. Thus, we use the principle of directional solidification which requires that the metal in the mold cavity first solidify farthest from the gate progressively toward the gate or source of fluid metal. This fluid metal "feeds" the parts of the casting progressively as the metal cools and solidifies, producing a solid, dense casting. The centrifugal force greatly magnifies this feeding action and produces a still greater metal density in the casting than would otherwise result.

3. From Fig. 1, we can see that at 1000 ft. per min. peripheral velocity the equivalent head of a centrifugal casting would be thirty feet! This is equivalent to a pressure of 102 lb. per sq. in. We compare this with the customary static casting having a head less than one foot high. From this, we can realize that a better feeding action results, so that it should be possible to feed through lighter metal sections into heavier sections more readily than in static casting.

DIRECTIONAL SOLIDIFICATION REMEDIES

4. Certain configurations of castings which do not inherently produce directional solidification may have this condition remedied. It can be done by the use of pads, auxiliary gates, chills or blind heads. However, a casting of non-uniform metal sections might require such elaborate pads, auxiliary gates, chills and blind heads as to increase the cleaning cost to a high figure. This type of casting "cannot be centrifugally cast".

5. Certain characteristics are desirable in vertical centrifugal casting machines, such as a simple, variable speed control;

strong, rigid construction; a facile method for loading and unloading the machine; a brake for rapid deceleration and safety features for the protection of the workmen.

6. When sand molds are used, particularly green sand, it is usually necessary to begin the pouring at a low speed and when the mold is partly or wholly poured, to increase the speed to that required. Because of the desirable and necessary adherence to the principle of directional solidification, molds should almost invariably be poured during rotation—even if the speed is only 5 r.p.m. This insures the proper distribution of "hot" and "cold" metal in the mold for best feeding action. When many different sizes and types of castings are made on the same machine, as is done in a jobbing foundry, a wide range of speed is essential. Machines should have continuously variable speed control. The speed change should be easy to perform, quick to react and capable of simple adjustment.

STURDY MACHINES

7. Machines should be sturdy. It is ofttimes necessary, or desirable, to spin castings which are not symmetrical or which are not symmetrically arranged about the axis of rotation. Sometimes two or more different castings are made in the same mold

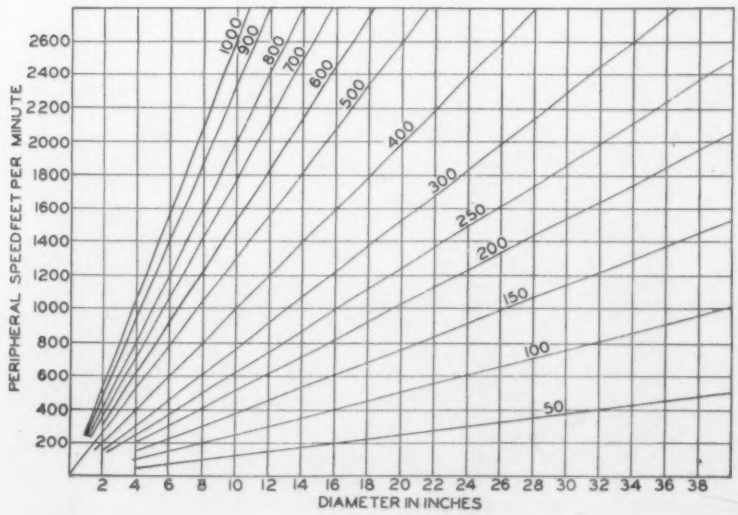

FIG. 2—GRAPH ILLUSTRATING THE APPROXIMATE PERIPHERAL VELOCITY TO BE USED ON CASTINGS OF VARIOUS DIAMETERS.

by the pressure method*. This causes an unsymmetrical arrangement which results in an unbalanced condition. Very bad balance will cause vibration which will have a detrimental effect upon the castings. However, if the machine is strongly built no vibration will be apparent.

8. The number of machines required for a given production is dependent upon the time consumed in casting each mold. Therefore, a simple, rapid arrangement for loading and unloading is essential for economical production, inasmuch as the spinning time is controlled by the length of time it takes for the metal to solidify. In practice, the spinning time will vary from 2 to 10 minutes—averaging about 3½ minutes. With an efficient brake and a satisfactory rapid method for loading and unloading the machine, 6 minute cycle may be maintained. This refers to molds too large and heavy to handle manually. Smaller molds, which can be manhandled and which require a shorter spinning time, can be changed more quickly. The use of permanent metal molds will still further reduce the spinning time.

DESIGN—A SAFETY FACTOR

9. Poorly designed centrifugal casting machines and equipment can be very dangerous to use. All clamping arrangements should be designed to tighten with, or to be unaffected by, centrifugal force. Molds should be firmly clamped to the table as unbalanced molds may otherwise fly off the table when the machine is in operation. Guards should be used about all machines to protect workmen from molten metal which will spray from the runner cup if it is poured too full. Some guards open on a hinge, Fig. 3; roll on a track back upon itself, Fig. 4; and some are lifted overhead while changing molds.

USING GREEN SAND MOLDS

10. Centrifugal castings may be made in green sand or dry sand molds. When green sand molds are used, flasks—which are preferably round—are required. Various methods are used to fasten the green sand mold to the table of the centrifugal casting machine.

1. Two pins are fastened to the table over which the flask is lowered. The cope and drag are held together by clamps in the usual manner.

*Janco, Nathan, *"Centrifugal Casting"* METAL PROGRESS, April, 1941, pp. 432-434.

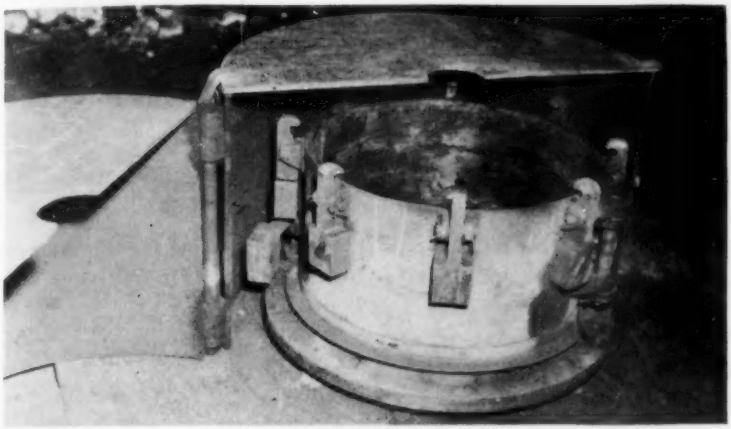

FIG. 3—GUARD FOR CENTRIFUGAL CASTING MACHINE THAT OPENS ON A HINGE.

2. A device similar to a lathe chuck is fastened to the table. The cope and drag are clamped together in the usual manner. The green sand mold is lowered onto the table and the clamps are tightened to hold the mold.

3. The green sand mold is pushed on a roller conveyor into a flask body which is fastened to the table. Rollers are also used in the machine to facilitate movement of the green sand mold. The flask body opens in half on a hinge. A cover, which holds a runner cup, serves to distribute equally the pressure from the clamping arrangement to the mold. The

FIG. 4—A GUARD THAT ROLLS BACK ON A TRACK. NOTE THE CONVEYOR AT RIGHT RUNS UP TO THE MACHINE TO FACILITATE HANDLING OF MOLDS.

clamping arrangement which is a part of the flask body, keeps the cope and drag in firm contact. (Fig. 4)

USING DRY SAND MOLDS

11. When dry sand molds are used, flasks are not required. Many methods of handling dry sand molds on the machine are used;

1. The dry sand molds are placed in a jacket somewhat similar to that used in conjunction with snap flasks. The jacketed mold is then carried to the machine and lowered to the table. Clamps hold the cover on the mold and also fasten the mold firmly to the table.

2. The dry sand molds are rolled on a roller conveyor into the machine in which rollers are incorporated. Using a flask body of this type, both dry sand and green sand molds may be used in the same machine interchangeably.

12. There seems to be a great deal of interest in the speeds used, especially among those not practicing centrifugal casting. Generally, the spining speed is not critical. An average satisfactory rotative speed is 1000 ft. per min. based on the greatest diameter. From Fig. 2, one can very easily find the proper rotative speed. In some castings, excessive speed may result in cracks in the periphery. This is really a form of hot-tear caused by the excessive speed. Rotation causes tensile stresses in the periphery of the casting. If this tensile force exceeds the strength of the casting during the period it is cooling through its range of low strength, the casting will crack. The remedy is simply to reduce the rotative speed until the cracks are eliminated. However, all cracks should not be attributed to excessive speed. Cracks also result from the customary causes, such as too hard or strong a mold material, fins, abrupt change in section, and other causes.

13. Table 2 describes a list of miscellaneous castings comprising sprockets, valve parts, pressure castings, sheaves, gear blanks, and similar items.

14. Four different castings have been selected to illustrate (Fig. 5) the economy which may be obtained by centrifugal casting, such as valve bodies, high pressure fittings and sheaves. The molding costs are practically the same whether produced centrifugally or statically. If dry sand molds are used for centrifugal casting, the molding costs might be increased as much as 50 per

Table 1

CHART SHOWING INCREASED YIELD FOR SOME MISCELLANEOUS CASTINGS

Casting	*Weight, Lb.*	*Static Yield, Per Cent*	*Centrifugal Yield, Per Cent*
A	61	39.0	79.7
B	40	53.4	74.1
C	17	49.2	75.5
D	31	38.0	67.4
E	60	36.3	77.0
F	31½	41.5	64.3
G	63	40.0	79.3
H	44	36.4	73.3
I	13	22.2	73.8

FIG. 5—VARIOUS CASTINGS MADE BY THE CETRIFUGAL CASTING PROCESS.

Table 2

SAVINGS DUE TO INCREASED YIELD OF CENTRIFUGAL CASTINGS

Casting	*Wt., Lb.*	*Wt. Metal Poured Statically, Lb.*	*Static Yield, Per Cent*	*Cent. Yield, Per Cent*	*Wt. Metal Poured Cent., Lb.*	*Wt. Metal Saved, Lb.*	*Savings (Value Metal at 2c per Lb.)*
1	66	190	34.8	78.6	84	106	$2.12
2	44	121	36.4	73.3	60	61	1.22
3	61	156	39.0	79.7	77	79	1.58
4	31	82	38.0	67.4	46	36	.72
5	17	34	49.6	75.5	22.3	11.7	.23
6	60	165	36.3	77.0	78	87	1.74

cent due to the higher grade of sand mix used and the cost of drying.

15. Table 2 illustrates the savings due to the increased yield. The savings per ton of shippable castings vary from $27 to $64. For this group, the average is $54.60.

Molding Costs

16. The cost of a green sand mold is ordinarily the same whether prepared for static or centrifugal casting. If dry sand molds are used for centrifugal casting rather than green sand, the molding cost may be higher, resulting in a reduced saving. There is an appreciable saving in the cleaning room due to the lack of heads. This reduces the amount of cutting, chipping and grinding. The additional cleaning room saving might be offset by operating costs, depreciation on the investment in centrifugal casting equipment and possible increased molding costs due to the use of dry sand molds.

17. In these days of striving toward higher quality, reduced costs and increased production, centrifugal casting is gaining impetus. Castings with increased density and enhanced metal structure rival forgings. Higher yields and decreased cleaning costs result in reduced over-all costs. Due to the increased yield obtained by casting centrifugally, there is a corresponding real increase in foundry capacity. With no increase in melting capacity, an increase in the tonnage shipped results.

DISCUSSION

Presiding: C. E. Westover, Burnside Steel Foundry Co., Chicago.

Chairman Westover: I recently made the statement, in connection with centrifugal casting, that if we people studying this method would only be frank, compare notes, and discuss the problem, we would break away from the idea that we have developed something special in our shops, or that we really have some secret process.

As Mr. Janco has pointed out, there are a number of advantages to centrifugal casting, the matter of yield being one. The work is progressing to where the method is becoming practical from a standpoint of molding and casting.

Mr. Janco made a statement concerning the pouring of metal into

the molds at five revolutions. Would he explain how he is going to change the speed of his machine from 5 to 1000 r.p.m., at what stage of the operation is he going to change that speed and just what is accomplished through speed changes?

MR. JANCO: When I spoke of 1000 I meant 1000 ft. per min. peripheral velocity; not 1000 r.p.m.

The graph used in Fig. 2 of the paper is a direct mathematical calculation that anyone can make, and is used to calculate the speed of rotation. It answers the question, at what speed shall we rotate this casting?

The diameter of the casting, in inches, runs along the horizontal line and the peripheral velocity along the vertical line. If the casting was 12-in. in diameter, the proper rotative speed would be about 325 r.p.m. Many molds are poured at zero, or a low speed, and then increased in speed after the mold is filled.

Many castings are poured at the spinning speed. That is, we would bring the mold up to 325 r.p.m., and pour the metal in there and spin the mold until solidified. It is necessary in a machine to have flexible speed control. We must be able to adjust the speed required for the particular casting. Since some castings require a change of speed during the pouring operations, it is necessary to have an easy method for adjusting that speed.

After the casting has been poured we want the mold stopped. We do not want to waste time waiting for the machine to slow down, so, we should have a brake on the machine to bring it to a stop rather quickly, but not abruptly. That way we are liable to break the casting.

Sometimes it is necessary to leave the casting in the mold for a few hours allowing it to cool, so it will not crack during shakeout.

The reason for pouring at a lower speed is to eliminate or reduce scabbing, cutting and erosion. A large casting poured at high speed would cut the mold and we would have to scrap the casting. For that reason we rotate at low speed when pouring, and later the speed is increased. We have two periods in which to increase speed; immediately upon the pouring of the casting, or wait until the mold is full and then increase the speed of rotation. It varies depending upon the type of casting being made.

EMIL PRAGOFF[1]: Did the author find any more rapid venting of gases from molding sand because he is spinning the mold? Do you select sand of certain fineness or do you have to alter your core making, or mold making, procedures appreciably?

I know of a man in Birmingham making pipe with the centrifugal process and he uses a permeability as high as 700, and has a good reason.

[1]Sales Supv., Hercules Powder Co., Wilmington, Del.

It was to compensate for the chilling effect of the roll. They want the heat to get out through that belt very fast and they want it to collapse very rapidly.

MR. JANCO: In horizontal centrifugal casting you have no heads or gates. You know that the casting weighs 100 lb. and you pour 100 lb. of metal into the mold. Very rapid chilling from the outside of the casting towards the center of rotation is desired in order to avoid any centerline weakness—that is in horizontal centrifugal casting.

In vertical casting, where we have a gate or a combination gate, or head, or riser, we have this feeding continuously, so that we are not so interested in having high permeability. In fact permeability as low as 10 is used.

Permanent molds are being used and the mold may be heated. In certain castings it is necessary to provide vents for the air in the mold cavity too, but usually the force is so high that it will force all of the air or gas that is in the mold out. There is little trouble encountered from that source, and it is possible to pour the castings with very thin metal sections because when you pour the metal into the mold, you pour it under great centrifugal pressure.

It is desirable to pour centrifugal castings rather quickly. The rate of pouring is just the same as it is in static castings. We found the rate of pouring should run between 3 lb. per second and 5 lb. per second.

In making the mold, the facing sand is used, and it is backed up in the normal manner; just as though you were making a normal mold. You probably would use exactly the same sand that you are using in your foundry for static castings.

The only difference might be, since you do not care about permeability, you would ram the core or the mold harder, in order to get a hard sand face. The necessity of pouring at low speed and then increasing the speed later is to eliminate the erosion due to rotation.

Since you have a single gate and all of the metal passes over the same place in the sand, it is necessary to have the sand harder to eliminate erosion and scabbing.

HOWARD MASON[2]: Do you build these machines yourself?

MR. JANCO: Yes, in our own shop.

MR. MASON: Is it always necessary to guard these machines? Would it not be possible to have a table without a guard which might adapt itself more readily to castings or molds of varying heights?

MR. JANCO: The necessity for a guard is to make the process safe for the workers. When you have about a ton or a ton and a half of sand and metal rotating, you have a considerable force, and at 1000 feet a minute, if anything goes wrong you want your workmen protected.

[2]Personnel Mgr., Symington Gould Corp., Depew, N. Y.

The machine is limited to molds which are that diameter, but is not limited in depth. You can pour any depth within that range of the flask body. If some job comes in and you decide that you need a smaller flask, or you need a larger flask, and you require larger molds, you just take out four bolts, take that whole flask body off, and slip on another one. This operation just takes a few minutes since there are only four bolts to change, and everything remains perfectly balanced.

MR. MASON: You have never tried casting in cores on the machine?

MR. JANCO: I mentioned that most castings are made in dry sand molds, or practically made in cores.

MR. MASON: There is no re-enforcing flask around the core, in other words, the core is outside of the mold?

MR. JANCO: Usually there is a flask or something put around it. They slip the dry sand mold (which is really a core) into the flask body. The flask body holds it in the exact center of rotation so that it makes it easy to pour.

You go to great trouble to make sure you have a perfect fit at the parting or you might have a run out. Using a flask body, if the metal does run out, it would run out on the flask body which would immediately chill it and that would stop your run out. All you would have wasted is the metal in the fin.

Your yield would be reduced from 75 per cent to 70 per cent, but you still would not hurt the mold.

DAVID L. PARKER[3]: Mr. Janco mentioned a weight of 2,000 lb. Was that the total weight of the mold flask and everything, or was that the maximum weight of casting that you make?

MR. JANCO: The weight of 2,000 lb. was really round figures. The machine I had in mind takes a mold about 25-in. high by about 3 ft. in diameter. The sand alone would weigh 1,200 lb. The casting that would go in the mold would weigh up to 800 lb. or 1,000 lb. or it might only weigh 150 lb. so that you could pour castings that weighed up to 800 lb., which would make the whole thing weigh about a ton.

MR. PARKER: What is the heaviest casting you have made this way?

MR. JANCO: The heaviest that I remember was about 300 lb. I know there are castings being made that weigh as much as 600 lb.

MR. PARKER: Do you feel that this method will ever be used in 7000 and 8000 lb. castings?

MR. JANCO: I think sometime in the future we will be making them that heavy, but I do not know anyone who is doing it now.

CO-CHAIRMAN WESTOVER: Our thinking along the line of centrifugal casting has been stimulated in recent years by the articles that were

[3]General Electric Co., Everett, Mass.

published by R. S. McCarroll, Ford Motor Co., Detroit, Mich., and the work that his company is doing. However, this centrifugal and vertical casting process is not new. The Davis wheel that was cast by the American Steel Foundries is an old process that was used in production. I do not know the date that they started that process. It was discontinued in later years because of new processes of manufacturing wheels, but it was successful.

WALTER WRIGHT[4]: In answering to Mr. Parker, we cast gear blanks in our plant up to 72-in. in diameter and that weigh as much as 4,500 lb. We also cast gear blanks down to 8-in. in diameter and weighing only about 10 lb. I see no reason why 7,000-8,000 lb. castings cannot be made centrifugally. The problem, as I see it, would be to have a machine strong enough to handle the job, and then doing the necessary experimental work to assure a sound casting.

CO-CHAIRMAN WESTOVER: Would you care to say anything about the speeds or the peripheral speed of some of those jobs?

MR. WRIGHT: We do not run our speed as fast as Mr. Janco. We try to maintain 600 surface ft. a min. We find that works out very well for gear blanks, which is the bulk of our work.

We cast centrifugally, perhaps 80 gear blanks a day of all diameters and weights. We have been doing this for about 16 years. We have tried higher and lower speeds and we find that we get the most satisfactory results at around 600 surface ft. a min.

We use some dry sand cores which are slipped into a jacket, but the great bulk of our work is green sand made in the flask because the flasks are so much easier to handle and so much easier to center on the machine than is core work.

CO-CHAIRMAN WESTOVER: In connection with the spinning of the molds; in your large molds, do you pour metal with your machine in motion?

MR. WRIGHT: We do not spin until the mold is filled with metal. Originally we did rotate the mold while we were pouring but we had so much trouble with sand in the castings, and other complications, that we finally arrived at our present method which is to spin the mold immediately after it is filled. We have been getting the most satisfactory results in this manner.

H. S. REAM JR.[5]: Does the author's method of casting centrifugally mean that he can pour at a lower or higher temperature for an ordinary static casting?

MR. JANCO: The pouring temperature seems to have little effect upon the casting. It does not seem to affect the structure. It is possible to pour castings at a lower temperature centrifugally than you do stati-

[4]Secretary, The Sawbrook Steel Castings Co., Cincinnati, Ohio
[5]General Supt., Shenango-Penn Mold Co., Dover, O.

cally. If you have a thin section, the metal will not run in a static casting, while in a centrifugal, you have the force that will make it run much better; so you can pour it at lower temperatures, appreciably lower.

Concerning the pouring of large castings, I would like to say just one thing. It is just as convenient, or just as suitable, in many cases, to pour at zero speed, and then speed up. Because you have very heavy metal sections, and it makes no difference at all, especially in gears, where your metal is going to run out to the outside periphery. It makes a lot of difference as far as dirt and erosion and scabbing are concerned and you get exactly the same effect, because it takes possibly a minute or a minute and a half to pour a casting of that size and then you start the machine going and the metal in the mold has not started to solidify so that you gain everything that you would in centrifugal casting, and you might eliminate the trouble you have due to dirt and erosion.

W. G. MIXER[6]: Has the author had any experience in permanent mold work, that is , constant work, and what length the life of the dies might be? I ask this because we are producing brake drums without an outside shell. It is a permanent mold casting procedure and the length of life of the mold is questionable. They vary a great deal and I wonder what factors might tend to lengthen or shorten the life of those dies.

MR. JANCO: If there was somebody here from the Ford Motor Co., they could give you much better information. Since there is not, I will have to give you the information second hand.

It is my understanding that this company, where they centrifugally cast gear blanks on permanent molds, have a life of 1,000 parts; 1,000 castings per mold. The design of the mold is very important in the life.

I have had no experience with permanent molds, but I have spoken with the men of the Ford Motor Co. and they claim that the shape or design of the mold is very important. If it is a simple shape, such as that used for a gear blank, why they can repair that mold with 2 hours machine time. Make a perfectly new mold merely by putting it in a lathe and machining it off.

If the mold is complicated, the life will not be as long because the mold will probably only last half as long and the expense of repairing it, or putting it in first-class shape again, would be practically that of making a new mold. Therefore, if you are making very simple gear blanks, the mold life is longer than if you are making complicated molds. In fact, I know of one case where the mold life is about three castings.

A. W. GREGG[7]: Mr. Janco said that he had an increase in density. Has he any figures showing how much of an increase?

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[6]Fdry. Supt., Buick Motor Co., Flint, Mich.
[7]Fdry. Engineer, Whiting Corp., Harvey, Ill.

MR. JANCO: I was afraid somebody was going to ask me something metallurgical about centrifugal casting. All I can say is we have been trying to accumulate information metallurgically, concerning the difference between centrifugal casting and static casting. We do have some information. We have some microphotographs and so on, but we do not know anything definite. Therefore, I do not like to say anything except this; there is no difference in the tensile strength and yield point of a casting made out of the same metal made statically or centrifugally. However, there is a very definite increase in the impact strength, which means an increase in the fatigue strength of a casting made centrifugally over that made statically.

I think that would be a very fruitful field for investigation. I have read the literature about casting non-ferrous metals centrifugally, particularly bronze, and there is a five per cent increase in density. People who are buying centrifugal castings, who formerly bought the exact same thing cast statically, claim their bills are higher because the castings weigh more.

We are accumulating data now to determine just how dense the castings are. It seems to me you could do it by taking test bars of probably the same metals cast each way. The best method would be to get an average of a few thousand or hundred castings made statically and centrifugally, and fully know their weight. Then you could tell.

HENRY U. ROSS[8]: I understand that one of the advantages of centrifugal castings is that any dirt that flows in with the metal is concentrated in the center of rotation and can be eliminated. Now, if the metal is poured while the mold is stationary, I would think that the dirt would be carried to the middle or the outside of the casting. What I would like to know is, when you start rotating the mold at high speed, would the dirt go back to the center of the gate so that it can be removed?

MR. JANCO: That is a very good point. Molds made for pouring statically or centrifugally are apt to be dirty. If you pour a static casting, the same static casting that you would pour centrifugally, and the mold is dirty, the dirt will accumulate at any point where it becomes lodged. It might be under the surface—it usually is—and the first indication that the foundry has that there was any dirt in the casting is when the machine shop machines it and sends the casting back because it has a void there due to sand or slag. In centrifugal casting, it is usually the case that the dirt will accumulate toward the center, so that in the cleaning room, the dirt will be located and the customers will obtain solid dense castings. The dirt, if it is lodged in the center, can be chipped out and welded, or the casting can be scrapped. However, usually, the castings in general will be cleaner as far as the customer is concerned. The castings in the foundry, if the foundry practice is poor, will be dirtier, because all the dirt is accumu-

[8]Metallurgist and Fdry. Supt., Union Screen Plate Co. of Canada, Lennoxville, Quebec, Canada.

lated in one spot, instead of being distributed throughout the metal of the casting.

MEMBER: With respect to pouring speeds; we found just the opposite to what Mr. Janco found. By increasing speed we could eliminate these tears and not by slowing down.

CO-CHAIRMAN WESTOVER: It had something to do with the density and it seems to be eliminated when the speed is increased on small castings.

MR. JANCO: Were those castings pressure cast?

MEMBER: Yes.

MR. JANCO: In referring to cracks or tears I meant those encountered in casting semi-centrifugal castings similar to a gear blank or sheave. It probably would not happen in a gear blank because your metal section would be heavy, and you would have a lot of cross sectional area to resist the centrifugal force which is putting the periphery in tension.

In pressure casting, if you increase the speed, the tendency is to force the metal to refill any crack that would occur. I had reference to making sheaves or round objects which had thin sections in the periphery.

MEMBER: In our experiments we found that copper was a great aid in the direction of eliminating hot tears. By an addition of 0.80 to 1.00 per cent copper the metal seemed to have improved fluidity. With the increased fluidity there is a possibility that an increase in metal density occurred; also copper might impart a toughening effect to the matrix adding sufficient hot strength during some phase of weakness encountered when the metal was solidifying. I do not know how accurately this claim can be substantiated as I am merely quoting the results we obtained and how we were able to eliminate tears in certain castings. Possibly an addition of nickel would accomplish what the copper did. The Ford Motor Co. use a copper addition in light section castings and they claim that it improves fluidity of metal measurably.

MEMBER: A question comes up about segregating centrifugally cast castings. Has anyone had any experience with what might be termed segregation due to centrifugal casting?

MR. JANCO: No, except what I have read in literature. In nonferrous metals at very high speeds there is a tendency to separate the lead from the copper. In the manufacture of gun barrels, it is claimed that there is a gradation in the carbon content from the outside of the casting toward the central axis.

Flame-Hardening Malleable Iron

By Stephen Smith*, New York, N. Y.

Abstract

Flame-hardening of malleable iron is a relatively new hardening process for that product. In this paper, the author outlines the hardening of black-heart and pearlitic malleable irons by the oxyacetylene flame using various type tips and time-temperature relations. Two methods of flame-hardening are outlined: (1) The application of the flame to the whole surface to be hardened and then quenching, a method termed spot hardening and (2) progressive flame-hardening in which the flame is moved progressively over the surface to be hardened and the surface immediately quenched by a stream of water at the proper distance to the rear of the flame. The flame-hardening of black-heart malleable iron may be accomplished in two ways: (1) To form a martensitic structure and (2) to form a cementitic structure. Methods of accomplishing the structural changes are outlined. By means of photomicrographs, the author shows the importance of the proper time-temperature relation in producing the structure desired. The flame-hardening of pearlitic malleable iron to produce a martensitic matrix also is discussed, as is the use of proper quenching medium and the influence of design on castings for flame-hardening.

1. Industry is constantly on the lookout for new materials or processes which, when applied to existing materials, will improve their physical properties, reduce cost of manufacture, increase their service life and in general widen their field of use.

2. For industrial applications where castings of fair strength, good ductility, easy machinability, possessing resistance to shock, and low cost of manufacture are important considerations, malleable iron is preeminently suited. It is finding ever increasing use because its mechanical and physical properties make it a desirable

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material from many angles of consideration. It is stronger and more ductile than ordinary gray iron and it is more readily and more economically cast into thin sections and intricate shapes than carbon steel. When heat treated, it combines the simplicity and adaptability of castings with a strength and reliability similar to forgings.

3. The addition of surface hardness to its existing properties opens new and greater fields of application to malleable iron. It makes possible the production of a material possessing a combination of properties such as a hard wear-resisting surface and a tough ductile core. The ability of malleable iron to undergo various heat treatments, further adds to the wide range of combined properties that may be obtained and further increases its potential field. By heat treatment, the strength and toughness of the core may be varied to produce the desired combination with surface hardness for any particular service requirement. The oxyacetylene flame offers an excellent and practical means to produce the surface hardness whereby such a combination of properties may be obtained.

4. As the variety of grades of malleable irons is too numerous to be discussed individually, the treatment of the subject shall be confined to the application of the oxyacetylene flame for hardening malleable irons in general, whose structure consists of ferrite and free carbon in the form of temper carbon with or without various amounts of combined carbon in the form of pearlite or free cementite. By the application of proper technique, it is possible to successfully flame-harden all of the various types of malleable irons met in commercial practice, to a greater or lesser degree, and uniformity of hardness.

COMPARISON OF FLAME-HARDENING STEEL AND MALLEABLE IRON

5. First we shall compare the flame-hardening of steel and cast iron with that of malleable iron. The surface hardening of steel, by the oxyacetylene flame, is accomplished successfully on material containing an adequate amount of carbon (0.35 per cent carbon or more) to obtain an appreciable degree of hardness. In flame-hardening cast iron, the presence of combined carbon in the matrix is required for successful results. The process employs the oxyacetylene flame merely as a heating medium in an operation analogous to furnace hardening and involves no change in chemical

composition of the material, such as the introduction of carbon as in case hardening.

6. However, the flame-hardening of black-heart malleable iron and the pearlitic malleable irons containing free ferrite may be compared to case hardening. The operation involves the carburization of the ferritic matrix before complete and uniform hardness can be obtained. No chemical change is involved and the surface to be hardened is not packed in carbonaceous material or subjected to a carbonizing gaseous atmosphere, but the temper carbon uniformly distributed in the matrix of ferrite grains acts as the carburizing agent. The ferrite is in a much more intimate contact with the carburizing material than in case hardening. Therefore, the process of hardening is one of pure diffusion. However, it is not due to the intimacy with which the carbon is in contact with the iron that rapid carburization is achieved, but due to the nature and fineness of the temper carbon itself. Close contact of carbon with iron is also present in graphitic-ferritic cast iron, but it is not so easily possible to achieve a carburization of the matrix from the graphite by the application of the proper temperature for short durations of time.

METHODS OF FLAME-HARDENING

7. In using the oxyacetylene flame, two general procedures can be employed. The selection of one of these will be determined by the nature of the part to be hardened and the results desired.

8. The first method is the application of the flame to the whole surface to be hardened and may be termed spot hardening. The entire surface is brought up to the hardening temperature, then the flame is removed or extinguished. This is followed immediately by quenching in a bath or spray. The surface may be heated by a multiflame tip or burner, large enough to cover the whole surface or a smaller burner may be used and oscillated to heat the entire surface.

9. The depth of hardness in this method is controlled by the amount of heat or size of burner used, and the time of heating.

10. The second method involves heating the surface to be hardened by the application of the oxyacetylene flame in a progressive manner. The flame is moved progressively over the surface and followed immediately at the proper distance to the rear by a

quenching stream. The surface is raised to the hardening temperature by the intense heat of the oxyacetylene flame and the quench following produces the hardness. This procedure generally is used for hardening surfaces of extended length and the burner employed is equal in width to the surface being hardened.

11. Hardness depth is determined by the size of burner and the speed of travel over the surface.

Degree of Hardness

12. The degree of hardness obtained in both methods will be determined by the nature and composition of the malleable iron matrix, the temperature to which the surface is raised, and the time required to reach this temperature. The time and temperature to give the desired results can be coordinated by the selection of the proper size burner.

13. Rockwell hardnesses ranging from C42 to C58 have been obtained on various types of malleable irons. File hardness is obtained on hardened malleable and cast iron at a hardness of Rockwell C55, whereas the equivalent file hardness on a steel surface occurs at a hardness of Rockwell C60.

FLAME-HARDENING BLACK-HEART MALLEABLE IRON

14. Because of the great diffusion speed of temper carbon, it is possible to produce a surface hardness on black-heart malleable iron without materially affecting the core by employing the intense heat of the oxyacetylene flame for heating. This hardness may be produced in the following ways:

(1) Heating in such a manner that the temper carbon will partially go into a gamma solution and from which martensite is formed on very rapid cooling.

(2) Heating to an appropriately high temperature and rapid cooling in which cementite hardening takes place through the crystallization of cementite.

15. Black-heart malleable iron, because of its ferritic matrix, is the most difficult to flame-harden successfully to obtain uniform hardness. The manner and duration of heating will determine the uniformity of hardness that can be obtained. It is essential to heat at such a rate as to allow the temper carbon to diffuse as uniformly as possible through the matrix before quenching. Successful accom-

plishment of this will produce a martensitic structure and maximum surface hardness.

16. Maximum hardness is more readily accomplished by the first flame-hardening method described, that of heating and quenching. A proper size burner is selected which will produce the approximate surface temperature in the required time necessary to effect a uniform diffusion of the temper carbon through the matrix. The heating time generally will be less than one minute. Longer heating time will cause the heat to soak into and affect the core. Very rapid heating, on the other hand, will cause the temper carbon to dissolve in the matrix and will result in the formation of cementite and cementite hardening on quenching.

17. Martensitic hardening of black-heart malleable iron is more difficult to produce by the progressive flame-hardening method, as the time of heating is relatively short, casting sections are relatively thin and the amount of heat necessary to produce a case hardness is relatively large. Slow speeds on thin sections will cause complete heat penetration, thereby affecting the core structure. Slower hardening speeds giving longer heating time can be successfully used on the thicker sections only.

18. Martensitic hardening is also difficult to accomplish on castings containing a skin or decarburized surface. In heating such a surface in progressive flame-hardening, it is possible to obtain a martensitic structure just below the decarburized surface, while at a still greater depth, cementite hardening will occur. This is evident from Fig. 1. The solution of the temper carbon through the matrix at the lower depth has been carried out almost to completion. The high temperature reached produced a matrix of eutectic composition which resulted in the formation of ledeburite on rapid cooling. The low carbon surface of the casting showed no visible indication of surface fusion to indicate that such a high temperature had been reached.

19. This surface was hardened at a speed of 4 in. per min. with a water quench following at a distance of $\frac{3}{4}$ in. Therefore, the time of hardening was approximately 12 sec. A $\frac{1}{8}$-in. depth of hardness was obtained on a section having a thickness of $\frac{1}{2}$-in. A scleroscope hardness of 65-70, corresponding to Rockwell C47 to C50, was obtained on removing the decarburized surface.

FIG. 1—BLACK-HEART MALLEABLE IRON PROGRESSIVELY FLAME-HARDENED AT A SPEED OF 4-IN. PER MIN., X100. (REDUCED ONE-THIRD IN REPRODUCTION.)

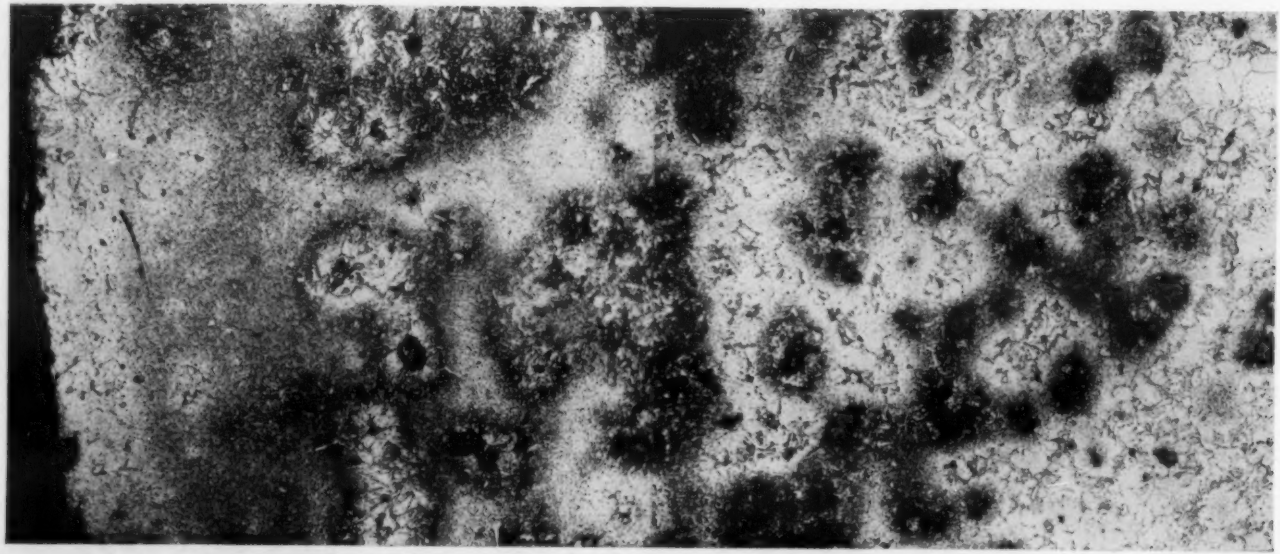

FIG. 2—BLACK-HEART MALLEABLE IRON PROGRESSIVELY FLAME-HARDENED AT A SPEED OF 5-IN. PER MIN., ×100.

20. Hardening a second casting of the same composition using the same burner and traveling at a higher speed of 5-in. per min., corresponding to a heating time of 9 sec., an incomplete diffusion of temper carbon was obtained with the resulting structure shown in Fig. 2. It will be noted that with the short difference in time prevailing in the two speeds, a matter of 3 sec., the faster hardening speed and correspondingly lower surface temperature prevented the temper carbon from diffusing completely throughout the matrix, resulting in a non-uniform hardened structure. Islands of strongly carburized areas, which are martensitic in structure, have formed around the temper carbon nests. These island areas have not had time to overlap each other. Between the islands, carburization has taken place to a lesser degree. Evidently a sufficiently high temperature was reached for a short interval of time to cause the formation of cementite adjacent to the temper carbon, as shown in Fig. 3. This is a photomicrograph of the same area shown in Fig. 2. The number of these formations was few and only occurred in the temper carbon nodules immediately under the decarburized surface skin. Surrounding this formation the structure is martensitic. A scleroscope hardness of 50 to 65 or Rockwell C38 to C48 was obtained upon removing the decarburized surface.

FIG. 3—CEMENTITE ADJACENT TO TEMPER CARBON NODULE IN FIG. 2. X500.

21. The complete removal of a decarburized surface will enable the selection of a proper size burner and thereby produce better control of the surface temperature, which will result in a more uniform structure and hardness where maximum hardness is desired.

22. A research investigation in Germany[1] on the flame-hardening of black-heart malleable iron, disclosed that a martensitic hardness can be produced by quenching from a temperature of 1850°F., while for cementite hardening, a temperature of 2000°F. should be used.

23. The investigation also reveals that martensitic hardness in black-heart malleable undergoes tempering at a temperature of 212°F., while cementite hardness resists tempering up to a working temperature of 525°F. This is significant in that parts subjected to service under temperature should be hardened to produce a cementite hardness.

FLAME-HARDENING PEARLITIC MALLEABLE IRON

24. Pearlitic malleable irons, because of the nature of the matrix, containing combined carbon of various contents, require simply heating and quenching to produce satisfactory martensitic hardening by either method described. Here, as with black-heart malleable, cementite hardening also may be accomplished by heating to appropriately high temperatures. When appreciable amounts of free ferrite compose the matrix, a slightly longer time of heating is required to produce maximum hardness. Because of the rapid diffusion of the temper carbon, this time is relatively short, amounting to a few seconds as previously shown.

25. Figures 4 and 5 show a pearlitic malleable iron before and after flame-hardening. In Fig. 4, the unhardened iron consists of an almost complete pearlitic structure, only a small amount of ferrite is present around the temper carbon.

26. Figure 5 shows the martensitic structure of the flame-hardened surface. The surface was flame-hardened by simply heating and quenching in a bath of water. The time of heating was 15 sec. and a file hard surface of Rockwell C55 was produced to a depth of $\frac{3}{32}$-in.

27. Figure 6 shows a malleable iron, similar in composition

[1] Superior numbers refer to references at the end of this paper.

FIG. 4—UNHARDENED PEARLITIC MALLEABLE IRON, x500.

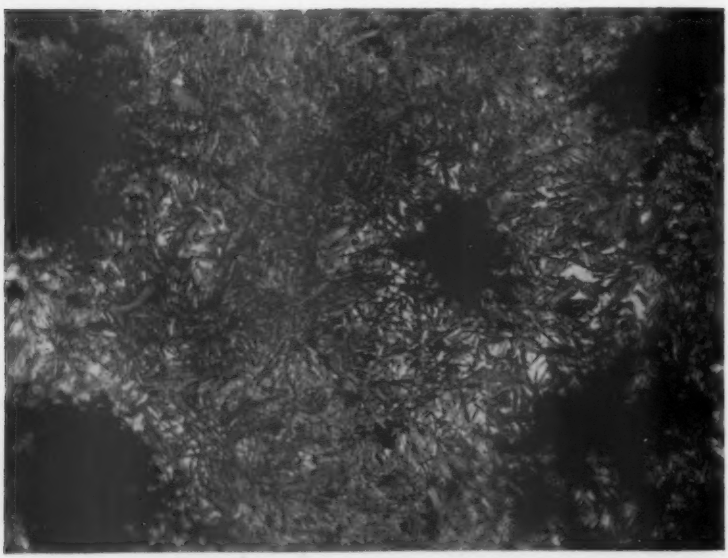

FIG. 5—FLAME-HARDENED PEARLITIC MALLEABLE IRON, x500.

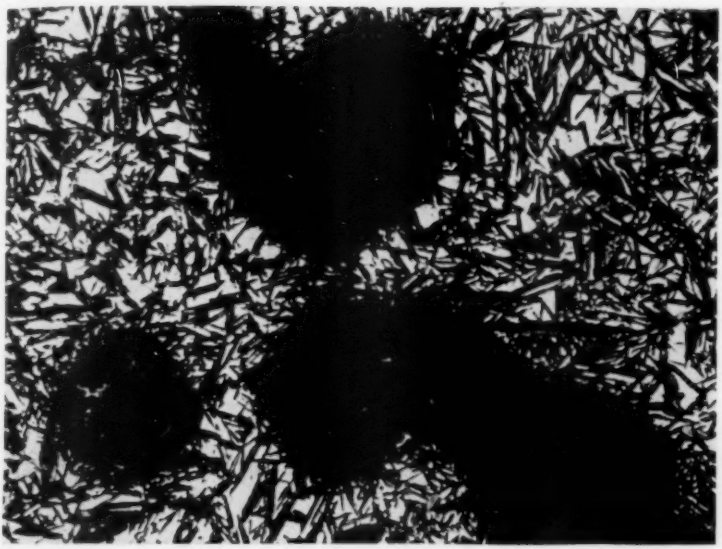

FIG. 6—PEARLITIC MALLEABLE IRON FLAME-HARDENED AT HIGH TEMPERATURE, X250.

FIG. 7—ENLARGEMENT OF TEMPER CARBON NODULE IN LOWER LEFT-HAND CORNER OF FIG. 6, X1000.

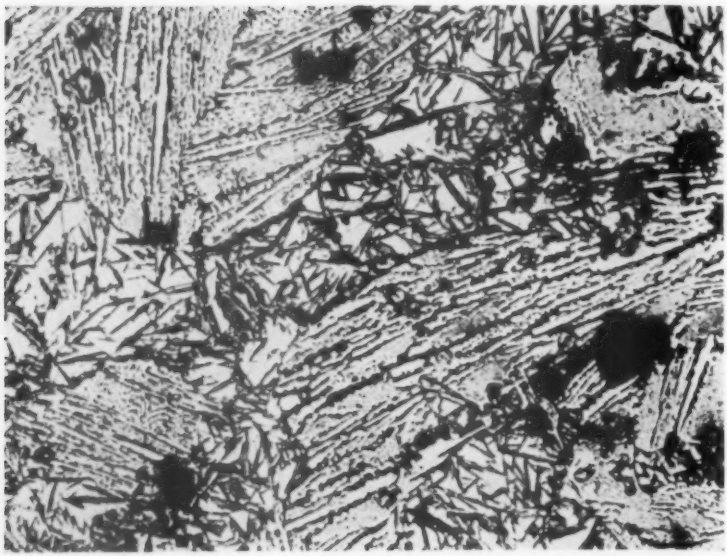

FIG. 8—PEARLITIC MALLEABLE IRON FLAME-HARDENED AT SWEATING TEMPERATURE, X250.

to that of Fig. 5, which was heated for the same length of time to a higher temperature. The structure is coarse martensite in a matrix essentially austenitic. Diffusion of temper carbon is progressing rapidly, as shown in Fig. 7, which is an enlargement of the temper carbon nodule in the lower left hand corner of Fig. 6.

28. Heating a casting of the same composition to a still higher temperature for the same length of time, resulted in a structure shown in Fig. 8, consisting of austenite, ledeburite and coarse martensite. It will be noted that almost complete solution of temper carbon has occurred. The hardness of this structure was found to be Rockwell C50. Incipient melting of the hardened surface was evident.

29. From the foregoing, it is evident that any desired hardened structure may be obtained, depending on the speed of heating and quenching.

QUENCHING MEDIUM

30. Slightly higher hardness results are obtained by hardening in oil rather than in water; however, oil can be used in the

heating and quenching method only, wherein the part is dropped into an oil bath after heating. Oil is excluded from the progressive method because of its flash characteristics.

31. When it is not required to obtain maximum surface hardness, a soluble oil solution may be used for quenching in progressive hardening. It is an excellent quenching medium, but requires a pumping system to supply it to the quenching jets under pressure, as well as a suitable tank for receiving the coolant after using.

32. Compressed air, under various pressures, may be used as a quenching medium, but it is more difficult to control and distribute evenly over the surface to produce a uniform quench.

DESIGNING PARTS FOR FLAME-HARDENING

33. Flame-hardening, like all new processes, is subjected to misapplications, particularly with respect to parts unsuited in shape or section to the process. When flame-hardening is contemplated, parts should be designed to permit the use of the process to the best advantage. Wherever possible, all sections to be flame-hardened should be uniform in thickness. Variations in mass, particularly when using the progressive method of flame-hardening, will cause variations in surface temperature and depth of hardness, and will result in unequal cooling, a non-uniform structure in the case, and distortion.

34. The surfaces to be flame-hardened should be simple in shape, to permit the simplest type of burner to be used. Large surfaces, containing projections greater than $\frac{1}{16}$-in. high, should be avoided when progressive hardening is required, as the projections will heat faster than the lower surface and overheating of the projections will result. Where hardness in corners or grooves is desired, generous fillets should be introduced.

SUMMARY

35. The flame-hardening of black-heart malleable iron is possible because of the ease with which carburization of the matrix by the rapid diffusion of temper carbon in ferrite takes place.

36. The flame-hardening of black-heart malleable iron is more readily controlled by the heating and quenching method than by the progressive method. The decarburized skin should be removed to obtain best results.

37. Pearlitic malleable irons are more readily flame-hardened by either the heating and quenching or progressive method, as they simply require heating and quenching to produce a uniform structure.

38. The surface structure of malleable iron may be transformed by flame-hardening to suit the purpose for which the material is to be used. A martensite or cementite hardness can be obtained.

39. Martensite hardness undergoes a tempering at 212°F.

40. Cementite hardness resists tempering up to a working temperature of 525°F.

41. The depth of hardness may be controlled to retain a tough ductile core.

42. A surface hardness of Rockwell C42 to C58 may be obtained on malleable iron by flame-hardening, depending on the nature of the matrix and the structure of the case desired.

References

[1] Kritzler, Prof. Dr. Ing. Gottfried, and Roll, Dr. Franz, "AUTOGENES HARTEN VON GUSSEISEN UND TEMPERGUSS," FORSCHUNGSARBEITEN, *Schweissens und Schneidens*, pp. 122-130 (1939).

[2] "ALLOYS OF IRON AND CARBON, Vol. II," by Frank T. Sisco.

[3] "*Symposium on Malleable Iron Castings*," A.F.A. and A.S.T.M. (1931).

[4] "*Symposium on Pearlitic Malleable Cast Iron*," A.S.T.M. (1936).

[5] Joseph, C. F., "*ArMa Steel*," IRON AGE, May 25, 1939.

DISCUSSION

Presiding: C. F. JOSEPH, Saginaw Malleable Iron Div., General Motors Corp., Saginaw, Mich.

E. C. MATHIS[1]: Would you say something about the means that you have used to overcome distortion and warpage in a piece where one dimension might be considerably larger than the other two and, also, the effect of the flame on surface corrosion?

[1]Metallurgist, Pickands Mather & Co., Chicago, Ill.

MR. SMITH: Warpage is rather difficult to control on all types of castings. Where you have castings of rather extended length and thin section, if you can place them in contact with material possessing considerable mass which will conduct heat away during the flame hardening operation, warpage can be reduced to a minimum. Another method that has been tried to reduce warpage was by immersing the casting in water, but the castings were relatively thin and the heat conduction was not rapid enough to keep that mass sufficiently cool to prevent the warpage, whereas if we can get that material on a mass, solidly, it will conduct the heat away sufficiently fast to prevent a good deal of the warpage.

Your other question was about corrosion. I am sorry to say that I do not have any information on the effect of flame hardening on corrosion resistance.

MR. MATHIS: I meant the resultant corrosion due to the flame hardening. How much effect upon the surface is produced by flame hardening and quenching? Is the finished surface a bright surface?

MR. SMITH: If you mean oxidation or scaling of the surface, no, there is not oxidation or scaling. That applies particularly to the progressive hardening method because in progressive hardening, you have the flames followed immediately by a quench and the enveloping flame keeps a reducing atmosphere on the surface at all times until the quench strikes it, which quenches it, therefore, there is no scaling or discoloration, In the heating and quenching method, a certain amount of scaling would occur, all depending on the length of time of heating and the length of time that is required to apply the quench after the flames have been extinguished or removed. If you apply the quench while the flames are still on the surface, you can reduce the scaling a great deal.

CHAIRMAN JOSEPH: In paragraph 13, the author mentions that a Rockwell hardness ranging from C42 to C58 has been obtained on various types of malleable irons. I do not know of any part that we have made within the last few years of malleable iron where we were able to get a Rockwell hardness as high as C58. In most cases, the Rockwell hardness has not been over C42 or C43. That is on a straight malleable iron. Where you have some combined carbon in the malleable, it is possible, of course, to get the hardness up as high as C62, providing the combined carbon is high enough to start with and the casting that is being heated and quenched is small. I have reference to a rocker arm that would have a combined carbon of about 0.33 per cent, heated with acetylene and oxygen up to a temperature of around 1650°F., which would take a very short time, not over six seconds. That would probably give you a Rockwell on the pad of the rocker arm of around C50. I do not know of very many applications where malleable iron is being flame hardened, that is, the straight malleable iron, not iron containing an appreciable amount of combined carbon in it to start with. I think the future of the pearlitic malleable iron industry is good, because pearlitic malleable can be flame hardened very readily. There are a number of parts that are being used today on motor cars that are being flame hardened, but in

every case that I know, the part is made of an iron containing a combined carbon of approximately 0.35 per cent or higher.

R. J. TEETOR[2]: We have successfully flame hardened special reamers or valve reseating tools in very small quantities. These reamers are of a form more readily produced in malleable cast iron than machined from a tool steel bar. The procedure is to machine the flutes and flame harden, after which the flutes are ground. From the standpoint of cost and adequacy for the purpose intended, these tools are quite satisfactory.

MEMBER: What was that combined carbon content?

MR. TEETOR: I cannot say. It was ordinary malleable iron of the typical analysis, nothing special. I do not know how deeply it was decarburized on the surface. The question just entered my mind during this discussion as to what effect the decarburization of the surface might have on successful flame hardening. A casting that is deeply decarburized on the surface, more so than would be normally desired, might present some difficulties in flame hardening as against a casting which has a very thin decarburized shell.

CHAIRMAN JOSEPH: I would think you would have trouble to harden the outside layer of a malleable casting. It would probably have to be machined first and then you would get some hardness, but not very much, possibly, especially if you had to be careful not to burn the outside layer. If there are any thin edges present, you naturally would have a tendency to overheat those edges.

G. A. SCHUMACHER[3]: We all have had some experience with the armour plate industry. To bear out what you have said, Mr. Joseph, we had to have that surface machined because of decarburization in the sections. The sections were about 1½-in. thick and we had some success in that line, in that we maintained the usual malleable hardness on the one side and obtained a Brinell hardness of 250 to 275 on the hardened side.

MR. SMITH: There is a considerable amount of work being done, or development being undertaken, on the flame hardening of cast metal alloys for armour plate, and with a considerable amount of success. To date, we do not know just how far this will go, or the complete results that have been obtained, because these are usually taken away to some arsenal or proving ground and shot up and we do not usually get full information.

MR. SCHUMACHER: Chairman Joseph, have you observed any experiments on electrical induction in this field, for rocker arms, to obtain proper hardness, for wearability and wear resistance?

CHAIRMAN JOSEPH: Rocker arms have been hardened by the electric induction heating method, just like cam shafts and gears and various other parts. That is being done every day and the results are equally as good as the flame hardening method.

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[2]President, Cadillac Malleable Iron Co., Cadillac, Mich.
[3]Metallurgist, Albion Malleable Iron Co., Albion, Mich.